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THE IMPORTANCE OF AIRCRAFT PERFORMANCE
AND SIGNATURE REDUCTION UPON
COMBAT SURVIVABILITY

by

John Den Langford, Jr.

September 1988

Thesis Advisor: Robert E. Ball

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The Importance of Aircraft Performance and Signature Reduction Upon Combat Survivability

by

John Den Langford, Jr.
Lieutenant Commander, United States Navy
B.S., Kearney State College, 1971

Submitted in partial fulfillment of the requirements for the degree of

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September 1988

Author: John Den Langford, Jr.
John Den Langford, Jr.

Approved by: Robert E. Ball
Robert E. Ball, Thesis Advisor

E. R. Wood
E. Roberts Wood, Chairman
Department of Aeronautics & Astronautics

G. E. Schacher
Gordon E. Schacher,
Dean of Science and Engineering

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An investigation was conducted to estimate the relative impact the six susceptibility reduction concepts of threat warning, tactics, signature reduction, noise jammers and deceivers, expendables, and threat suppression have on aircraft survivability, with particular emphasis given to tactics with increased aircraft performance and signature reduction. An essential elements analysis (EEA) was conducted for three representative scenarios, with and without threat warning available, to identify the essential events and elements in each scenario critical to aircraft survivability. The six concepts were assessed as to their relative impact on the essential events and an estimate of the aircraft's susceptibility and survivability was made. The results of the EEAs are presented in tabular format. The general conclusion is made that both increased aircraft performance, with threat warning available, and signature reduction, with and without threat warning available, play important roles in increasing aircraft survivability through a reduction in an aircraft's susceptibility.

DISCLAIMER

Throughout this thesis are direct quotations from The Fundamentals of Aircraft Combat Survivability Analysis and Design by Professor Robert E. Ball of ideas, concepts, formulae, definitions, as well as key descriptions of threats, scenarios, aircraft missions, and susceptibility reduction concepts and features. The justifications for this action are to continue the efforts by Professor Ball to standardize the discipline of aircraft survivability and to keep the overall classification of the thesis unclassified by using this open source publication.

The descriptions of the U.S. Navy's missions and functions, as well as portions of the aircraft mission descriptions, are taken from the unclassified sections of the appropriate Naval Warfare Publications (NWP) series.

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Additionally, and most importantly, I want also to thank my family for their unselfish and loving support during this ordeal. To my wife, Terri, who assisted with typing this thesis, and my two sons, "J.D." and Daniel Paul, thank you for keeping my motivation up and my priorities in proper perspective.

I. INTRODUCTION

A. SURVIVABILITY

A fundamental consideration in the design of military aircraft today is combat survivability. Without it, the ability of the aircraft to complete its mission is jeopardized. Aircraft combat survivability is dependent upon many factors, such as eliminating tailpipe exhaust smoke, employing optimal tactics, and/or using camouflage paint schemes, to name but just a few. A definition of survivability that includes all of the above factors is "the capability of an aircraft to avoid and/or withstand a man-made hostile environment." [Ref. 1:p. 1] The probability that the aircraft can survive the environment, P_S, is related to the probability that it will be killed by the environment, P_K, by

$$P_S = 1 - P_K. \qquad \text{[Ref. 1]}$$

The probability of kill is the product of the aircraft's probability of hit by one or more damage mechanisms, P_H, known as the aircraft's susceptibility and its conditional probability of a kill given a hit, $P_{K/H}$, known as the aircraft's vulnerability. Thus,

$$P_K = P_H \, P_{K/H}. \quad \text{[Ref. 1]}$$

Aircraft vulnerability is the inability of an aircraft to withstand one or more hits by the damage mechanisms. The more vulnerable an aircraft is, the more likely it will be killed when hit. To a large degree, vulnerability is a function of the design of the aircraft. By determining in advance those aircraft components that possess a high level or degree of vulnerability, steps may be taken in the design phase to reduce the overall vulnerability of the aircraft. This process is called vulnerability reduction, and it can significantly reduce the likelihood of an aircraft being killed if it is hit without sacrificing aircraft performance, weight, cost and combat effectiveness. [Ref. 1]

Susceptibility is the inability of an aircraft to avoid being damaged in the performance of its mission. Three major factors determine an aircraft's susceptibility: the scenario, the threat, and the aircraft itself. Thus, susceptibility is influenced by many things, and the reduction of an aircraft's susceptibility requires a thorough knowledge of the sequence of events, beginning with aircraft launch and initial detection by enemy sensors to the final impact by one or more damage mechanisms, such as missile warhead fragments and blast. Key elements in determining an aircraft's susceptibility are the enemy's threat surveillance activity, target identification, acquisition, tracking, and engagement, and the specific threat warhead characteristics, such as warhead size and fuzing. [Ref. 1]

B. SURVIVABILITY ENHANCEMENT

The two aircraft attributes that affect survivability are its susceptibility and its vulnerability. By reducing the levels of either of these two attributes, substantial increases in survivability can be achieved. [Ref. 1]

Survivability enhancement begins with a survivability assessment to include the systematic description, delineation, quantification, and statistical characterization of an aircraft's survivability during an encounter with enemy threat systems. It combines the results of a mission threat analysis that describes specific threats to the aircraft during expected scenarios, the results of a vulnerability assessment for the various threat propagators, and the results of a susceptibility assessment that outlines key parameters and variables such as aircraft radar and infrared signatures and propagator miss distances. [Ref. 1]

Susceptibility reduction is accomplished through a myriad of measures designed to impair the enemy's ability to engage a target. The susceptibility reduction concepts are threat warning, noise jammers and deceivers, signature reduction, expendables, threat suppression, and tactics. [Ref. 1]

Vulnerability reduction requires the incorporation of any design techniques or pieces of equipment that reduce or control the amount or the consequence of damage to the aircraft caused by one or more damage mechanisms. As with susceptibility, there are six concepts which reduce one or more aspects of an aircraft's vulnerability. These six concepts are component redundancy (with separation), component location, passive damage suppression, active damage suppression, component shielding, and component elimination. By careful examination, the appropriate reduction concept and/or concepts can be applied to prevent the loss of a particularly vulnerable component/system. [Ref. 1]

C. TACTICAL COMBAT AIRCRAFT DESIGN GOALS

A major goal in the design of tactical combat aircraft is to make them effective in any scenario. In order to be effective, an aircraft must be survivable. Survivability in combat is a function of many factors, such as fire/explosion protection, threat system capabilities, non-flammable hydraulic fluid, the scenario and, as emphasized today, aircraft performance and signatures. Improving the performance of an aircraft through improvements in speed and maneuverability can reduce exposure time in the threat envelopes, increase its capability to outmaneuver a greater number of enemy fighters and missiles, and result in reducing the aircraft's susceptibility, thereby increasing its survivability. In the context of the six susceptibility concepts, aircraft performance falls within the tactics concept because tactics are developed using aircraft performance as a primary consideration. [Ref. 1]

Signature reduction in the form of reduced radar cross section (RCS) or reduced infrared (IR) signature can also enhance aircraft survivability. Reducing the reflected or generated electromagnetic energy of an aircraft will adversely affect both a threat system's reaction time and its engagement envelope by reducing its ability to acquire, track, and engage a target. These delays reduce the chances the aircraft will be engaged during its mission, thereby improving its survivability. [Refs. 1,2]

It's important to note here that an aircraft's RCS is dependent not only on the frequency of the radar, but also on the aircraft's aspect relative to the radar that is tracking it. There is not just one value for the RCS of an aircraft. In most cases, aircraft radar signatures are normally assumed to refer to the average head-on aspect unless otherwise stated. [Ref. 3]

1. Performance Criteria

Among the many design goals, aircraft maneuverability and agility are receiving added emphasis today. Given an aircraft's state vector, "maneuverability can be thought of as the first derivative of this state, while agility is the second derivative" [Ref. 4]. Maneuverability can also be defined as the ability of an aircraft to change its velocity vector in both magnitude and direction. Although agility is not as rigidly defined as the other performance parameters, this characteristic refers to the ease and rapidity with which a particular aircraft's state of motion may be altered with confidence, precision and complete control. As evidenced by the Grumman X-29 and the multi-national X-31, future fighters must incorporate designs to reduce drag without compromising aircraft maneuverability or agility. These new goals are turning the aircraft industry's attention to that of exploring radically different concepts and designs in their quest to achieve the maximum aircraft performance possible. [Refs. 4,5,6,7,8,9, 10,11]

To gain the combat edge and achieve the desired design goals, specific performance criteria for a combat aircraft must be delineated and designed in the aircraft. Once the mission or missions have been decided upon, several performance criteria may be submitted to the potential airframe manufacturers by the cognizant authority (Naval Air Systems Command for the U.S. Navy). These criteria may include as a minimum the takeoff roll, landing distance, time to climb, sustained turn rate, and instantaneous turn rate. Achieving these criteria is the end result of the structural integrity, aerodynamic qualities, and powerplant characteristics of the aircraft. After careful analysis, final decisions regarding the engine size, types, and number, along with the wing characteristics, such as aspect ratio, wing loading and size, can be made which will result in meeting as many of the performance criteria as possible. The evolution of the aircraft design is an iterative process, requiring juggling of various innovative design features in order to optimize performance and achieve as many of the performance criteria as possible. [Ref. 12]

2. Aircraft Signature Reduction Goals

With the advent of extremely capable threat air defense systems, the emphasis on combat aircraft signature reduction has dramatically increased. Today several aircraft are being designed with reduced signatures as one of the major design goals. Through a reduction in radar cross section and infrared signatures, the aircraft becomes more difficult to initially detect, acquire, track, and engage. By significantly reducing the aircraft's RCS, the radar's maximum detection range may be significantly reduced. Additionally, reducing the aircraft's radiant intensity reduces an IR missile seeker's lock-on range. The key to successfully reaching these signature reduction goals is to achieve them without compromising the aircraft's performance, with the ultimate goal being increased aircraft survivability through reduced susceptibility. [Refs. 1,10, 13,14]

3. The Requirements for Threat Warning

Many of the susceptibility reduction features available to the aircrew operate most efficiently when specific information concerning threat operations is available. With timely and accurate threat warning, critical life saving actions, such as threat suppression, the employment of onboard chaff, flares, and deceptive jamming equipment coordinated with recommended evasive maneuvers, and the initiation of stand-off jamming can be taken. Thus, to adequately estimate the relative impact that increased aircraft performance and signature reduction have on aircraft survivability, these features will be analyzed with and without onboard threat warning available from either a radar homing and warning (RHAW) receiver or a radar warning receiver (RWR). To do otherwise may result in misleading or incorrect conclusions. [Refs. 1,5,9,12]

D. DESIGN CONSIDERATIONS FOR INCREASED AIRCRAFT PERFORMANCE AND SIGNATURE REDUCTION

1. Increased Aircraft Performance Considerations

Aircraft design is impacted by many design goals such as maneuverability, agility, and takeoff and landing requirements. By specifying the mission or missions of the aircraft, establishing design goals, and defining performance criteria, such as design Mach number, certain aircraft characteristics become fixed. For example, the design Mach number fixes the sweepback angle of the wing. This is a crucial design consideration for aircraft that will operate in the high subsonic and supersonic flight regimes. However, for supersonic flight, a high thrust-to-weight (T/W) ratio is required which will directly relate to an aircraft's maximum speed at various altitudes. Additionally, the aircraft's design will be significantly affected by the maneuverability and/or agility required. An aircraft with appropriate thrust-to-weight ratio and wing sweepback to meet the design Mach number may not necessarily meet the maneuverability and/or agility requirements. Thus, the design must also include computer controlled flight control systems which can rapidly adjust appropriate flight control surfaces to efficiently convert the energy available to maneuvering energy for optimum maneuverability and agility without compromising other performance factors. [Refs. 5, 8,12]

Over the past 40 years, an increasing demand has been made on engineers to reach more stringent design criteria that have resulted in some rather radical designs. Design trends in wing shape alone have produced aft swept and forward swept, delta, and variable sweep wing configurations. All are examples of designers attempting to meet the performance criteria while also meeting the specific mission requirements and profiles. Each aircraft is a compromise of many design factors and results in a unique aircraft best suited for a particular mission or missions. [Ref. 15]

2. Aircraft RCS Reduction Considerations

The radar cross section of an aircraft is a very complex parameter that is dependent on the size, configuration, aspect, and material composition of the aircraft, as well as the wavelength and polarization of the radar signal. Consequently, designers must be aware of the geometric shapes and materials that reradiate the incident radar signal toward the receiving antenna. For example, traditional engine inlet designs have been generally round or tetragonal shapes which cause multiple or sequential reflections of a radar signal. These multiple reflections produce individual returns that are added vectorially. Because the individual reflected signals will take different paths back to the radar receiver, each signal will have a unique phase. These phases may add or subtract to produce a nominal average RCS. Consequently, in the design of an aircraft, shapes that are relatively flat, dihedrals, and corners should be avoided, orientated, or located in an attempt to reduce an aircraft's RCS. This technique is called shaping and has been a driving force in helping to reduce radar cross sections of various aircraft. [Refs. 1,2]

Other RCS reduction design techniques include the use of radar absorbing material (RAM), passive cancellation, and active cancellation. RAM uses specially developed paints, such as ferrite-based and/or carbon based microwave absorbing materials, known for their lossy behavior, to act as radar absorbers. The remaining two methods are extremely ambitious, complex, and very frequency dependent. As a result of these problems, passive cancellation is no longer considered a practical technique. Active cancellation is a "smart" technique requiring a tremendous amount of parametric information concerning the signal characteristics so that a computerized system can generate a phase equal and opposite to the impinging radar signal resulting in cancellation. This technique has not been given wide publicity concerning its use as a means of RCS reduction in current or future aircraft. [Refs. 1,16,17]

The penalties for RCS reduction include cost, payload reduction, reduced range, added weight, and increased maintenance. However, since the bulk of the signature reduction technology is highly classified, the extent to which these penalties actually impact mission effectiveness is not known. [Refs. 1,17]

3. <u>Aircraft Infrared Signature Reduction Considerations</u>

Equally as complex as an aircraft's radar cross section is its infrared signature. The primary contributors to an aircraft's IR signature are the aircraft's engines, the engine exhausts, and the metal components that either reflect or emit electromagnetic energy with wavelengths between .77 and 1000 μs within the optical band. The most significant parameter to predict the levels of emitted radiation is the temperature of the particular component of an aircraft. Using an absolute temperature scale (Kelvin) as a reference, the intensity of radiation is a function of the temperature above absolute zero at which the aircraft components operate. With knowledge of the source temperature (degrees Kelvin), the wavelength, λ, corresponding to the peak spectral radiant emittance (watts/cm^2/μ) can be determined using Wein's displacement law mathematically expressed as

$$\lambda\ (\mu s) = 2893/T(K).$$

With the knowledge of the emitted wavelengths of the particular components of the aircraft, the important task of eliminating or significantly reducing the reflected electromagnetic energy in these bands begins. [Ref. 1]

Various techniques are used to reduce IR signatures. However, they all focus efforts on reducing the temperature, area, and emissivity or reflectivity of those components exploited by an IR weapon. Design considerations are most effective when incorporated early in the design process. Retrofitting infrared suppression can be costly from a performance perspective since some of the techniques require shielding, which adds weight, or employ jet exhaust cooling and mixing devices that may reduce the net propulsive force of the engine, as well as increase weight. Thus, backfitting an aircraft with IR signature reduction devices may be a very costly measure from both performance and financial viewpoints. [Refs. 1,14]

E. THESIS GOAL AND SCOPE

1. Goal

The general goal of this thesis is to present a logical approach for analyzing the effects of the six susceptibility reduction concepts on combat aircraft survivability. The effects of threat warning, tactics using increased performance, signature reduction (specifically RCS and infrared reduction), noise jammers and deceivers, expendables, and threat suppression will be examined to determine their impact on future aircraft survivability. This will be accomplished by conducting an essential elements analysis to identify time critical events in the scenario starting with the final undesired event, aircraft destruction, and culminating with the initial event, aircraft initial detection. The susceptibility reduction concepts will be assessed as to their relative impact on the critical events determined by the EEA. [Ref. 1]

2. Scope

The specific scope of the thesis will be limited to U.S. Navy tactical attack and fighter aircraft and their respective missions in overland and war-at-sea scenarios.

Due to classification considerations, the scenarios and mission descriptions will be generic, but as representative as possible. Additionally, the scope of the susceptibility reduction discussion will focus primarily on the effects increased aircraft performance and signature reduction, with and without threat warning available, have on aircraft survivability.

F. THESIS OUTLINE

The thesis consists of five sections. The first chapter discusses the emphasis of increased performance and signature reduction on aircraft design. The second chapter describes the U.S. Navy's missions and functions, and current and projected Navy attack and fighter aircraft missions. Chapter III discusses various threat systems and generic scenarios. Chapter IV is a susceptibility assessment using an EEA done in conjunction with a susceptibility reduction analysis. Chapter V contains the study summary and conclusions.

II. THE EMPHASIS OF INCREASED AIRCRAFT PERFORMANCE AND SIGNATURE REDUCTION ON AIRCRAFT DESIGN

A. INCREASED AIRCRAFT PERFORMANCE

One goal of aircraft designers has always been to maximize aircraft performance. Today's highly maneuverable aircraft are the result of increased technology in powerplants, wing design, and composite materials. As tactical jets have evolved, maximum performance in terms of both speed and thrust-to-weight ratios, combined with increased maneuverability, has been equated to effectiveness. Figure 1 [Refs. 9,10,15,18] shows representative U.S. Navy and Air Force attack/bomber and fighter aircraft performance trends since 1944 in terms of maximum high altitude (above 20,000 ft) Mach number and thrust-to-weight ratios. With the exception of the B-58A Hustler for attack/bomber aircraft and the F-5E Tiger for fighters, there is clearly a steady upward trend in terms of these two parameters. [Refs. 9,15,18]

Following World War II, the jet age saw the emergence of a variety of jet fighters which flew at moderately high subsonic Mach numbers. Soon after the Korean War, the first generation of swept wing aircraft capable of exceeding Mach 1 were introduced. With the increased speeds came increased thrust-to-weight ratios. By the mid 1950's, as Figure 1 shows, there were several jet fighter aircraft capable of

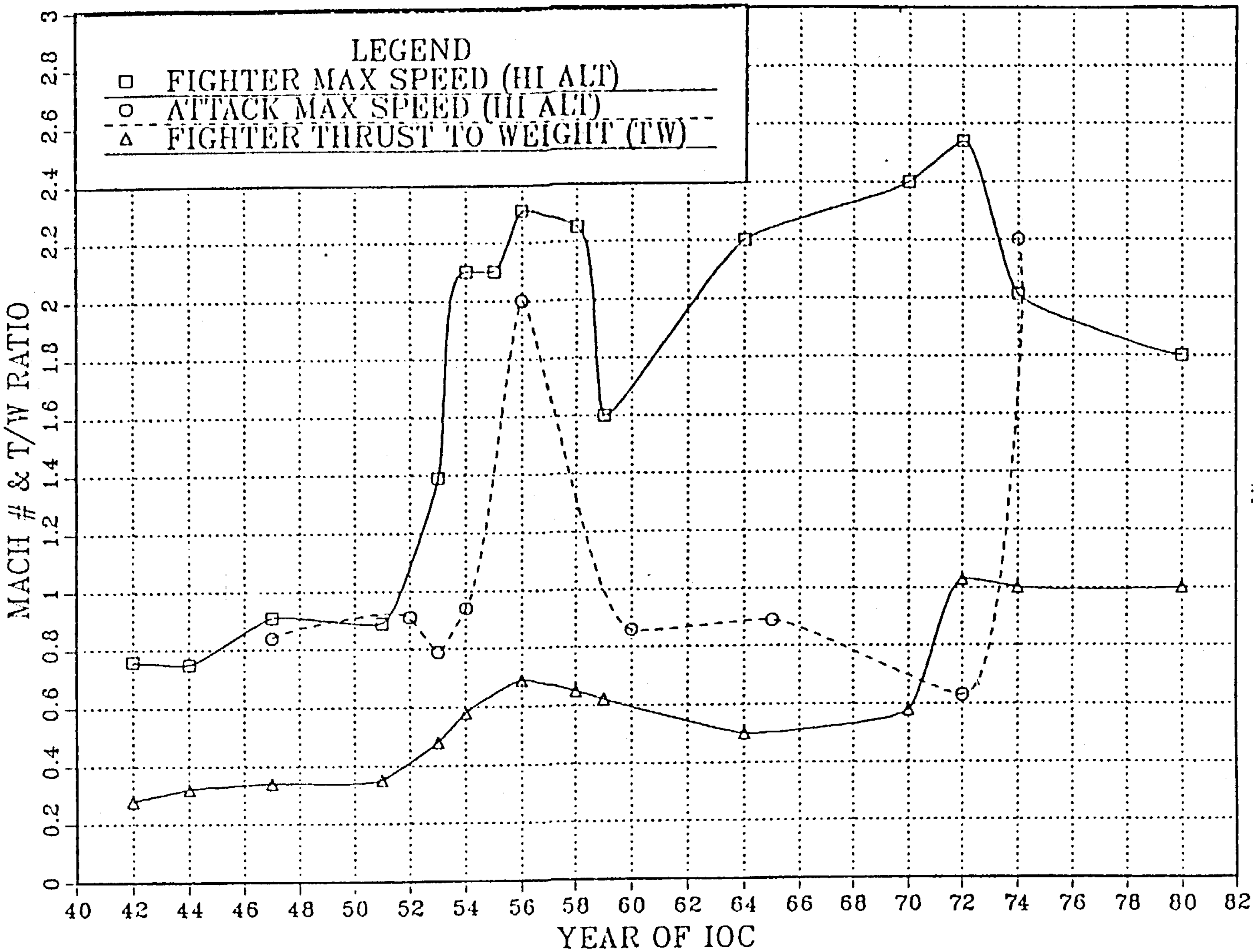

Figure 1. Aircraft Performance Trends Since 1944 [Refs. 9,10,15,18]

maximum clean speeds of better than Mach 1 at high altitude (above 20,000 ft) and nearly a 50 percent increase in thrust-to-weight ratios. Attack/bomber aircraft saw a similar trend, but were generally only capable of high subsonic Mach numbers. [Refs. 6,9,15,18]

With the increases in aircraft speeds, tactics shifted to that of an interceptor, hit-and-run, or deception profiles to take advantage of this capability. However, as a result of close-in air engagements brought about by the need for visually identifying the enemy during the Vietnam War, pilots began to emphasize the need for trading excess speed for maneuverability and agility. This increased maneuverability and agility could give a pilot the edge by allowing him to reach a firing solution for his air-to-air missiles or guns prior to his opponent doing the same. Additionally, extremely capable anti-aircraft artillery (AAA) and surface-to-air missile (SAM) systems were being introduced which meant speed was no longer a completely effective survivability technique. In fact, the excess speed combined with rather poor maneuverability and agility produced some disturbing effects. Newly developed evasive maneuvers for use against SAMs resulted in a large turn radius, with pilot's experiencing very high gravitational forces, commonly referred to as "G's." [Refs. 8,9,13,15,19, 20]

Consequently, the emphasis in design rapidly shifted to transferring this excess speed into maneuvering energy. By designing an aircraft capable of moderately high supersonic Mach numbers, but with outstanding "G" available at moderate subsonic speeds, a properly warned pilot's ability to outmaneuver more capable enemy fighter aircraft missiles and surface-to-air missiles could be significantly increased. The ability to intimidate the enemy and gain the advantage by either rapidly pointing your nose at the opponent or quickly reaching the firing envelope would contribute to a smaller P_K and an increased P_S. [Refs. 1,5,8,9]

In order to achieve increased maneuverability and agility, significant changes in aircraft wing structure and general design evolved. Variable geometry winged aircraft were developed to better convert energy into increased maneuverability and agility. Although the initial concept of variable geometry was first introduced in 1943, it was not incorporated into a United States tactical or strategic aircraft until the F-111A Aardvark was built. The variable geometry design allowed better lift at slow speeds and radically reduced wave drag in supersonic flight regimes. From the attack aircraft perspective, one other significant advantage was the excellent ride quality at very low altitudes and high speeds. This was truly a benefit since attack/bomber tactics then and now emphasize the use of terrain masking at low altitude for increased survivability.

However, variable geometry wings were not universally adopted primarily due to weight and perceived wing ordnance carrying difficulties. [Refs. 9,10,18]

Design trends have now focused on a camber fixed wing, but with the ability to change its profile in flight through the use of intricately controlled leading and trailing edge control surfaces. Today, an aircraft's wing planform and section profile can be optimized in flight to better adjust to rapidly changing threat scenarios. A variety of other innovations such as the predominance of twin tail configurations, canards, and slender wings to increase performance at high angles of attack were also introduced. Finally, by incorporating highly advanced computer controlled flight systems that instantaneously monitor and maintain optimal flight stability, the static stability requirement for jet fighters and attack aircraft could be relaxed allowing never before reached levels of maneuverability and agility to be achieved. [Refs. 1,9,10,18,21]

Vectored thrust is yet another method under study to improve pitch and roll maneuverability and agility. By replacing the tailpipe with two dimensional moveable sections encased around the exhaust and orienting them in such a way as to redirect the thrust vector, moments about the aircraft's center of gravity are created, thereby enhancing maneuverability and agility. [Refs. 1,9,10]

New advances in the development of composites, such as boron- and graphite-epoxy, have allowed engineers to develop aircraft structures that are lightweight, strong, and corrosion resistant. Tailored stiffness qualities are now making possible the introduction of forward swept wing fighters and attack aircraft. This unique configuration is of high interest due to the benefits of reduced drag and improved maneuverability and agility at virtually all Mach numbers. The obvious benefit of forward swept composite wings would be to build an aircraft with smaller, more efficient wings and engines to achieve the same or better performance as that of a conventionally designed aircraft. Thus, this aircraft could fly at relatively high Mach numbers with a smaller more efficient engine, and it could possibly also benefit from reduced radar and infrared signatures without sacrificing mission effectiveness. [Refs. 1,9,19,22]

Once the aircraft has been designed and built, one of the best tools for assessing its performance capabilities is the altitude versus Mach number (H-M) diagram. This diagram presents the maximum aerodynamic and structural characteristics of the aircraft as determined from flight testing and mathematical calculations. On a typical diagram, as shown in Figure 2 [Ref. 5], curves of an aircraft's specific energy, E_s, and its specific excess power, P_s, are plotted. E_s represents the sum of both the aircraft's potential

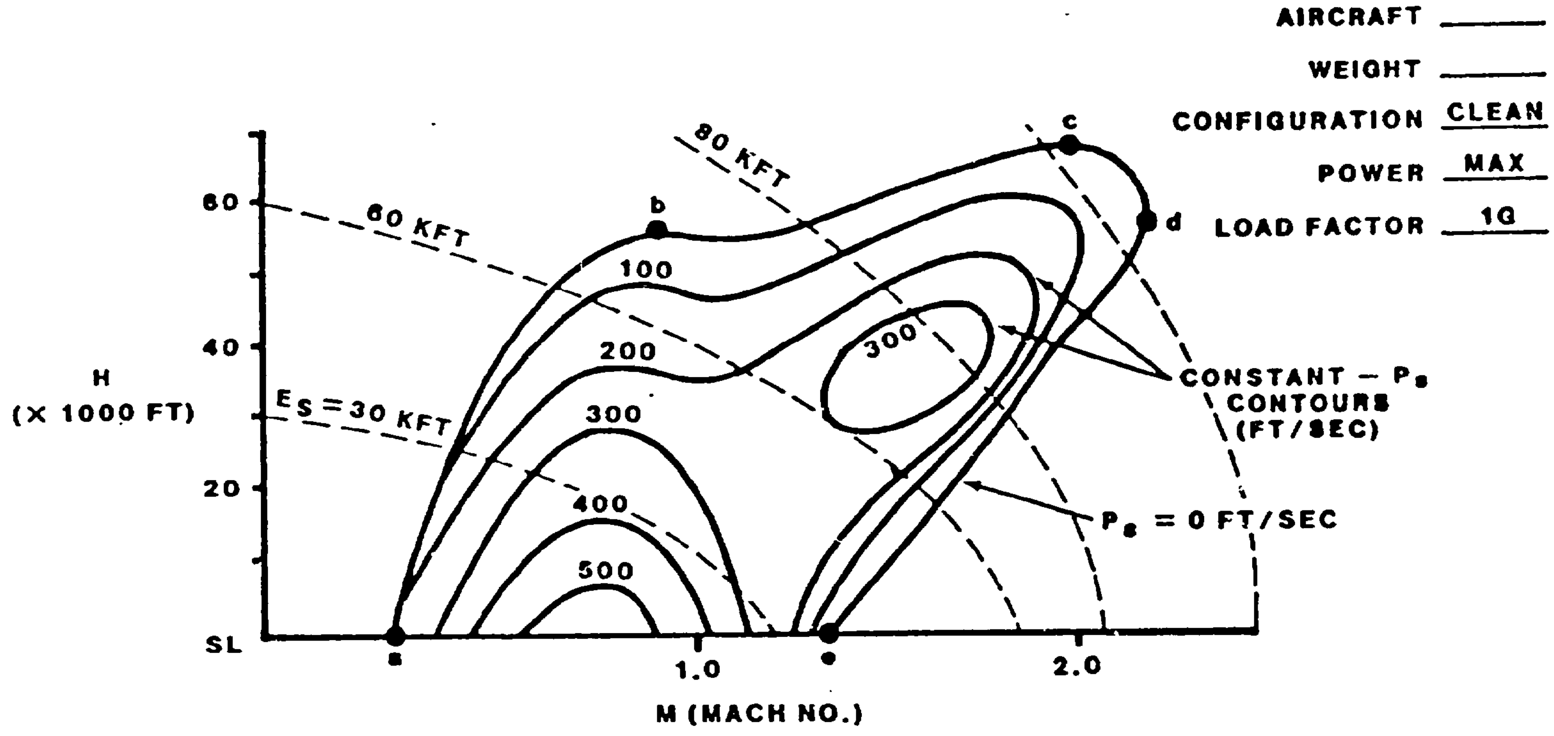

Figure 2. Typical H-M Diagram [Ref. 5]

energy, H, and its kinetic energy, $V^2/2G$, and can be mathematically expressed as

$$E_s(ft) = H + (V^2/2G)$$

where H equals the aircraft's altitude above some reference (ft), V equals the aircraft's true airspeed (ft/sec), and G equals the acceleration due to gravity (32.2 ft/sec^2). These lines of constant E_s on Figure 2 define the many speed and altitude combinations an aircraft may have for the same energy state. [Ref. 5]

A change in the energy state of an aircraft is done through the addition of power and for jets is generally the result of increased thrust. The added power results in a change in the aircraft's E_s. The ability of the aircraft to change the E_s is determined by its P_s, which is mathematically expressed as

$$Ps\ (ft/sec) = [(T-D)\ V]/W$$

where T equals total engine thrust (lbs), D equals the total aircraft drag (lbs), W equals the aircraft weight (lbs), and V equals the aircraft's true airspeed (ft/sec). [Ref. 5]

The P_s equation reveals that whenever the thrust exceeds the drag, the P_s for that aircraft will be positive, reflecting excess energy levels available for climbing or accelerating. Conversely, if drag is greater than thrust, energy levels will decrease, resulting in the inability of the aircraft to climb or accelerate. [Ref. 5]

A significant amount of information about an aircraft can be obtained from these diagrams. For example, by referring to Figure 2 and following along the $P_s = 0$ curve, the following information [Ref. 5] can be obtained at the appropriate letter:

a) minimum sustained Mach number for any altitude (.3M at sea level),

b) maximum sustained subsonic altitude and Mach number (56,000 ft at .9M),

c) maximum sustained altitude at any speed (67,000 ft at 1.95M),

d) maximum sustained Mach number at any altitude (2.2M at 55,000 ft),

e) maximum sustained Mach number at sea level (1.35M).

Other parameters, such as climb performance, controllability limits, and acceleration performance, can also be found on appropriate H-M diagrams. [Ref. 5]

Aircraft performance can also be measured by its ability to meet required criteria such as takeoff and landing distances, and turn performance. The two most common parameters for assessing turn performance are sustained "G" available and instantaneous "G" available. The former refers to turns accomplished while maintaining a constant energy level for an extended period of time, and the latter refers to the aircraft's maximum turn capabilities while losing or gaining energy at an explicit rate. In conjunction with these two parameters are the aircraft's turn radius and turn rate. Turn radius, R, usually measured in feet or miles, is a function of the aircraft's airspeed (ft/sec), V, and the load factor, n, which equals the lift force divided by the aircraft's weight. This can be mathematically expressed as

$$R\ (ft) = V^2/[G\ (n^2-1)\cdot 5]$$

where G is the acceleration due to gravity. Turn rate, usually measured in degrees per second, is also a function of the aircraft's airspeed and load factor and can be expressed mathematically as

$$\text{Turn Rate (degrees/sec)} = [57.3\ G\ (n^2-1)\cdot 5]/(V)$$

Figure 3 [Ref. 5] shows charts defining both turn radius and turn rates for a generic aircraft based upon true airspeed and specific values of L/W in terms of "G's." [Refs. 5,9, 12,23]

Improved performance is a very hot topic in almost any military or civilian arena today. Current trends and efforts only serve to emphasize the expanded horizons on which future aircraft performance will evolve.

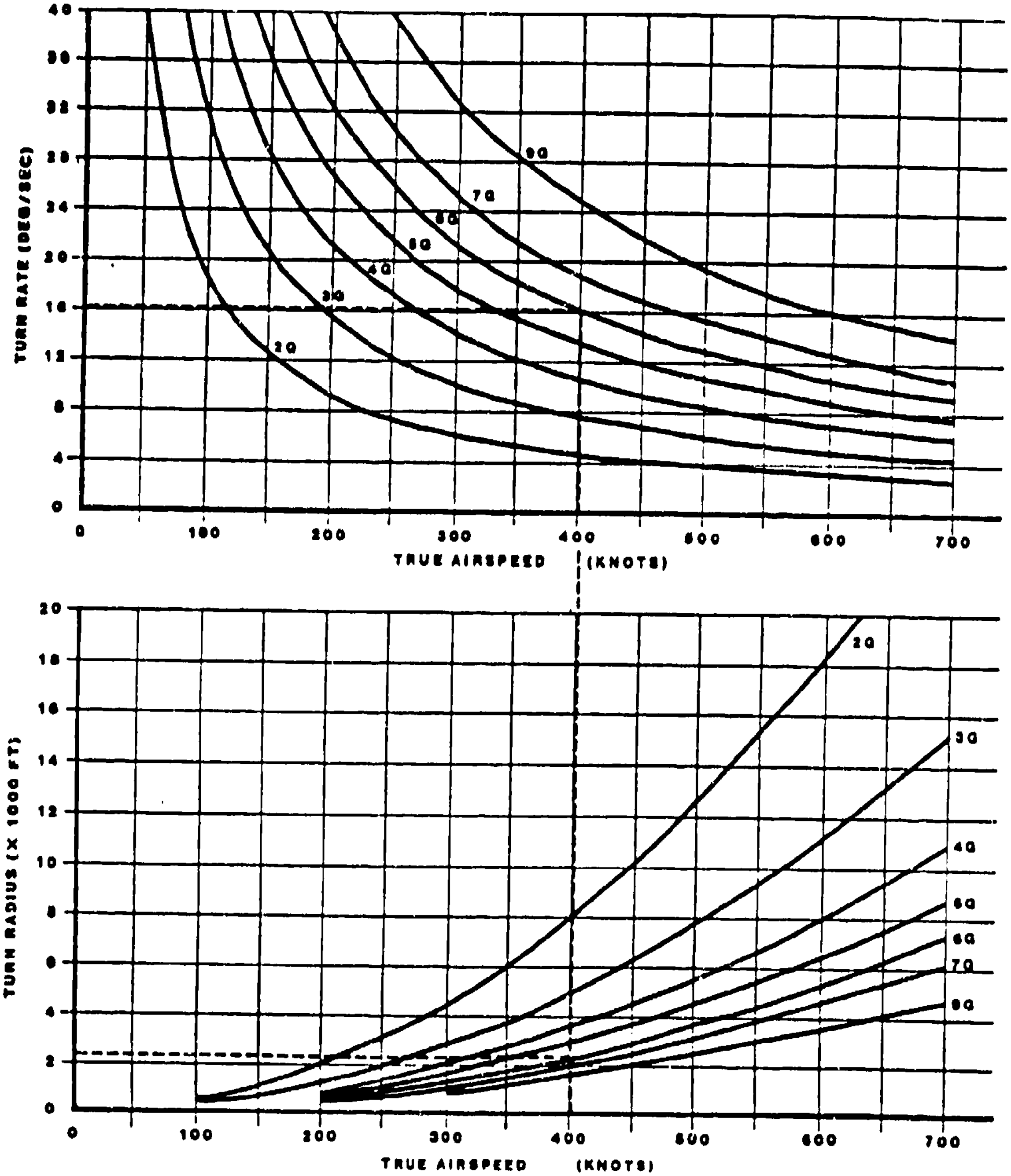

Figure 3. Aircraft Turn Performance [Ref. 5]

B. RADAR CROSS SECTION SIGNATURE REDUCTION

Today, aircraft design is taking a marked change in another direction. For the same reasons that attention has been given to increasing aircraft performance, the aircraft designer's attention has also been turned to that of reducing aircraft radar signature. The obvious benefit from RCS signature reduction is the reduction in reaction time by enemy defenses due to a reduction in the maximum detection range, R_{max}, of a radar. With the assumptions that multipath echoes are not present, the target is always in the line of sight of the radar, and all of the radar's parameters remain constant, the relationship between RCS signature reduction and R_{max} reduction is governed by the fourth root. This can be mathematically represented as

$$R_{max} = [(P_r\ G_r^2\ W^2\ \sigma\ F^4)/((4\pi)^3\ L\ N\ (S/N)_{min})]^{.25}$$

where P_r is the radar's peak power output, G_r is the radar's antenna gain, W is the radar's wavelength, σ is the aircraft's RCS, F is the multipath factor, L is the signal and echo power losses, N is the amount of inherent noise within the signal bandwidth of the radar's receiver and S/N is the ratio of echo power to the radar receiver's noise power often referred to as the signal-to-noise ratio. Consequently, the level of RCS signature reduction required to gain an appreciable reduction in the radar's maximum detection range is significant. For a 44% reduction in maximum detection range, a 90% reduction in RCS is required. This is shown in Table 1 for a generic fire control radar. [Refs. 1,2,10]

TABLE 1

RCS SIGNATURE REDUCTION IMPACT

Frequency	16 Ghz
Wavelength	.02 meters
Peak Power (Pr)	100,000 Watts (50db)
Antenna Gain (Gr)	10,000 Watts (40db)
Multipath Echoes (F)	1 (none)
Receiver Noise (N)	$2.5 * 10^{-16}$ Watts (-156db)
Losses (L)	15.85 Watts (12db)
Signal-to-Noise Ratio (S/N)	39.81 Watts (16db)

RCS (m^2)	% RCS Red	Maximum Radar Range (km)	% Range Reduction
100	-	189	-
10	90	106	44
1	99	60	68
.1	99.9	34	83

RCS signature reduction techniques rely on the use of shapes and materials to reduce the echo seen by the radar. This new technology has already been a major factor in the design of several aircraft. Specific information concerning the levels of RCS signature reduction, predicted effectiveness, and aircraft performance are classified at the highest levels, but open source literature indicates performance characteristics of the new generation of reduced RCS aircraft are in keeping with current fighter and attack aircraft. It's interesting to note that the Soviets in a September-October 1986 article in The Soviet Press: Selected Translations believe the advanced tactical fighter will incorporate signature reduction technology, be capable of cruising supersonically, and have exceptional maneuverability (8 "G's" at altitude). [Refs. 1,10,22]

In order to reduce the RCS of an aircraft, the portion of the incident radar signal reradiated in the direction of the threat radar's receiver must be reduced. As early as 1929, Mr. Jack Northrup demonstrated the feasibility of using a flying wing aircraft as a viable asset for military purposes. In 1944, aerodynamicists in Germany realized the significance of the flying wing design, not only from an aerodynamically efficient point of view, but also from the standpoint of the RCS reduction this design offered. Ironically, by about this same time Mr. Northrup had convinced the Army Air Corps that the "flying wing" should be built. [Refs. 1,2,3]

Designated the XB-35, this rather heavy bomber (gross weight of about 155,000 lbs) was a unique configuration requiring an exceptionally advanced control system and specially designed control surfaces called "elevons." These controlling surfaces were a combination elevator and aileron and gave the XB-35 its rolling, pitching, and directional control. Plagued by a series of both mechanical failures and vibrational problems, and with the advent of the jet age, this four engine, propeller driven aircraft was eventually shelved. Modified with four turbine engines and redesignated the YB-49, another attempt was made to conv ıce the Air Force the concept was valid. Doomed from the start for reasons of directional stability and a drastic reduction in range and payload capability, the YB-49 was scrapped. [Ref. 3]

The flying wing design was a logical choice that used the RCS reduction technique called shaping. The design had neither a fuselage nor large tail surfaces, virtually eliminating the reflective edges, corners, and boxy surfaces that adversely contributed to an aircraft's RCS. [Refs. 1, 3,16]

Signature reduction, or stealth as we know it today, most probably took its roots as early as the late 1950's under the sponsorship of the Central Intelligence Agency (CIA). Once it was decided to replace the aging U-2, the "Skunk Works" at Lockheed were approached with the prospect of designing an aircraft with exceptional performance and remarkably small head-on aspect RCS. The result was the SR-71 Blackbird whose design featured the elegance and sinister shape of a delta wing design with a blended fuselage that gave it the immunity to threats which it still enjoys today. The next step was obvious. If a large aircraft, such as the SR-71, was extremely difficult to detect by radars, could a smaller aircraft be made virtually undetectable? In the early 1960's, Firebee target drones were modified by the Ryan company to fly reconnaissance missions over China and North Vietnam and these later lead to the development of larger drones equivalent in size to a small aircraft. These drones proved to be extremely difficult to detect during tests in representative dense threat environments. [Refs. 10,16]

Of significant irony is that by the 1970's, none of the stealth aircraft built to date were capable of carrying ordnance or maneuverable enough to act as a fighter aircraft. Additionally, the military began to realize that a large percentage of the aircraft involved in major strikes during the Vietnam War were not bombers, but support aircraft tasked with supporting the bombers with jamming, chaff cloud seeding, and threat suppression with antiradiation missiles. As a result, Lockheed became even more deeply involved in stealth technology by designing and building the first stealth fighter prototype. By the end of 1973, the results of a proof-of-concept project called Have Blue paved the way for production of the first operationally deployed stealth fighters. Unofficially designated the F-19A, these fighters may be the first tactically deployed asset completely configured with RCS signature reduction as one of their primary susceptibility reduction techniques. [Refs. 7,10,16,22,24]

Soviet defenses, which now include over-the-horizon (OHT) systems that have extremely long wavelengths, pose some significant problems even for stealth aircraft. With these extremely long wavelengths, that are in some instances approximately the size of the target they are illuminating, the target itself will act as an antenna no matter what its shape may be. Thus, even stealth aircraft may be susceptible. To reduce this problem, special coatings and materials, such as reinforced carbon fibers were developed as RAM. The most likely application of this RAM would be to incorporate sections into the leading and trailing edges of the wing. [Ref. 16]

Today, aircraft designers have turned to using the RCS signature reduction techniques of shaping and RAM as a means of reducing aircraft susceptibility. Although much of the information on stealth is classified at the highest level, the significant level of interest in reducing aircraft susceptibility through RCS signature reduction is not at all a secret. [Ref. 16,22]

C. INFRARED SIGNATURE REDUCTION

In the early 1800's, Sir William Herschel discovered the existence of an infrared solar radiation band within the electromagnetic spectrum. Today, some of the most prolific weapon systems used worldwide are the relatively cheap, extremely effective, and easily operated infrared surface/air-to-air missile systems which passively exploit this band of the electromagnetic spectrum to detect and track airborne targets. As a measure of their impact, approximately 90% of all combat aircraft losses over the past 15 years are attributable to IR missiles. In fact, many of the historians and political analysts who are commenting on the recent pull-out of Afghanistan by the Soviets indicate that a prime reason for the pull-out was the losses inflicted by IR surface-to-air weapons. These loss statistics provide a strong incentive for the U.S. military to build aircraft with significant IR suppression and countermeasures techniques designed in the aircraft. Since the mid 1960's, significant studies have been conducted to better understand and control infrared radiations by various components of an aircraft, particularly those on rotary wing aircraft. [Refs. 14,25]

The two major sources of an aircraft's infrared signature are the propulsion system and the airframe surface. The relationship between the range at which seeker lock-on, R_{LO}, will occur and the aircraft radiant intensity is governed by the square root of the aircraft's radiant intensity. This can be mathematically expressed as

$$R_{LO} = [I/(L\ S_{MIN}\ (NEFD))]^{.5}$$

where I is the aircraft's radiant intensity at the aircraft in the direction and bandwidth of the IR seeker, L is the atmospheric losses or attenuation while propagating the distance R_{LO}, S_{MIN} is the minimum signal-to-noise required for target lock-on, and NEFD is the noise equivalent irradiance at the seeker that produces a signal equal to the internal noise. [Ref. 1]

Aircraft propulsion systems produce strong infrared signatures in a few bands as a result of the large amounts of CO_2 and H_2O in their hot exhaust. Once these hot gases are expelled from the engine, the atmosphere may scatter, absorb, or transmit the radiation from the CO_2 and H_2O. Scattering and absorbtion will generally deplete or attenuate the levels of this emitted radiation. [Refs. 1 and 25]

For both H_2O and CO_2, the IR bands that have the greatest absorbtion and emissivity are virtually the same. Because both these gases are in the jet engine's exhaust plume, a large amount of energy is radiated in these few bands. Ideally, the CO_2 and H_2O in the atmosphere would absorb this radiated energy because of the relationship between emission and absorbtion. However, the significant differences between the pressure and temperature of the atmosphere and that of the exhaust plume will result in a difference between the emission and absorbtion characteristics. For example, one primary absorbtion band for atmospheric CO_2 is around 4.3 μs, whereas the CO_2 from the jet engine plume is typically between 4.1 to 4.5 μs. Thus, the majority of the CO_2 will be absorbed by the atmosphere around 4.3 μs, leaving rather large spikes of residual energy on either side of this band, i.e., 4.1 and 4.5 μs. This non-absorbed energy is significant because CO_2 makes up the majority of the jet engine exhaust plume and the 4.3 μ band is one of the IR bands which passive IR threat systems can exploit. [Refs. 1,14,25]

One other key factor influencing the absorbtion of both H_2O and CO_2 is altitude. The relative amounts of each gas are reduced with altitude, but the concentration of H_2O is much more drastically affected by altitude. For example, the amount of H_2O present at 20,000 feet is less than 20% of that at sea level, whereas CO_2 will have the same relative concentration at 40,000 feet. These relative concentrations are also indicators of the relative absorbtion expected at those altitudes. Thus, at sea level, absorbtion of both gases is rather extensive; and as altitude increases, the absorbtion levels for H_2O and CO_2 diminish rapidly, with H_2O suffering the most dramatic reduction in absorbtion capability by the atmosphere. Consequently, the lock-on range goes up as the seeker/aircraft altitude goes up. [Refs. 1,14,25]

The major contributors to the IR signature of a tactical jet aircraft are the propulsion and airframe sources that either emit or reflect infrared energy. The emitted power is a function of aircraft Mach number, altitude, mission, the propulsion power setting, and the viewing angle the threat has of the infrared source. The four most common methods for reducing an aircraft's infrared signature include reducing the temperature of the source, the presented area of the source, and the surface emissivity and reflectivity of the source. [Refs. 1,14]

The most common techniques used to reduce the temperature and presented area of the propulsion sources of an aircraft are to reduce the exhaust plume temperature through cooling techniques, to cool and/or shield the hot metal parts, and to apply special coatings to critical metal components to further enhance the shielding effect. By far the most difficult item to cool is the engine exhaust plume. In general, cool ambient air must be mixed with the hot exhaust plume in order to lower the plume temperature. Turbojets may use compartment cooling or ambient ram air pumped into a coannular stream that surrounds the hot core. For turbofans, the task is much simpler since a readily available stream of cool air surrounds the hot exhaust gas and only needs to be mixed prior to exiting a common nozzle into the ambient air. Shaping the exhaust from a round cross section to that of rectangular shape, thereby increasing the exhaust tailpipe exit perimeter and generating vortices enhances mixing with the cooler ambient air surrounding the plume. A more simplified, but possibly less effective approach, is to incorporate an angled exhaust system to direct the hot exhaust at an angle to the flight path. [Refs. 1,14]

Engine exhaust components, such as the exhaust duct from the centerbody, the flame holders, the tailpipe, and nozzle wells, must also be considered in an IR signature reduction effort. For those components which may be difficult to cool, such as the turbine blades, shielding can be used to block the view that a potential infrared threat system's seeker may have of these components. In some cases, a turn in the exhaust system may be used to achieve this affect. [Refs. 1,14]

Radiation from airframe sources consists of emissions due to aerodynamically heated surfaces, hot metal components, and of reflection of incident radiation, or sun glint. There is currently no cooling technique available to reduce or eliminate aerodynamic heating. However, the impact of surface skin radiation at subsonic flight speeds on the aircraft's IR signature is considered minimal, and it is primarily an issue for any aircraft engaged in supersonic flight or any large aircraft flying at both low altitude and high speed. Hot metal components, such as oil coolers and heat exchangers, can either be shielded, insulated, or cooled by flow techniques. Sun glint can be caused by the shape of the airframe itself and may be solved by using flat surfaces as opposed to round surfaces; however, this may negatively impact the efforts to reduce the RCS of the aircraft. Other techniques, such as the use of infrared absorbing paint (IRAP), may offer a better solution. However, since this paint will absorb incident infrared radiation, the interior temperature will rise. This increase in temperature may preclude the use of certain heat sensitive equipment in those areas where IRAP has been used or vice versa. [Refs. 1,14]

The key to the IR signature reduction is to design in the techniques from the beginning, especially when confronted with a turbojet aircraft. The added weight and degradation to performance as a result of retrofitting the nozzles, ejectors, or other cooling hardware may not be acceptable in terms of the overall susceptibility of the aircraft. Shaping and painting may be a reasonable retrofit effort, but some added weight and possible adverse thermal effects may result. [Ref. 1]

III. THE U.S. NAVY ATTACK AND FIGHTER AIRCRAFT MISSIONS

A. U.S. NAVY MISSIONS AND FUNCTIONS

The U.S. Navy's mission, as set forth in Title 10, U.S. Code, "is to be prepared to conduct prompt and sustained combat operations at sea in support of U. S. national interests; in effect, to assure continued maritime superiority for the United States." [Ref. 26:p. I-3-1] In support of this mission, the Navy has two primary functions, sea control and power projection. To accomplish the mission and these two functions, the Navy has built a naval force centered around the aircraft carrier. The carrier is supported by a wide variety of surface, subsurface, and airborne assets. Each one of these assets is designed for and tasked with performing specific missions that will both individually and synergistically fulfill the Navy's mission. With these forces, the Navy must be able to conduct sustained operations at sea, with minimal advanced notice. Specific tasking includes maintaining control of vital sea lanes, keeping the lines of communication open, and achieving superiority on land, at sea, and in the air around those areas of naval operations. To accomplish these tasks, the Navy must be prepared to conduct operations at sea with carrier-based aircraft in order to prosecute and destroy enemy naval and land-based forces. [Ref. 26]

The two primary functions of sea control and power projection are very closely related. In order to maintain sea control, a projection of power may be required. Conversely, before power may be projected, sea control on, under, and above the ocean must be achieved. Without one, the other may not be possible. [Ref. 26]

1. Sea Control

This function is vital for any successful naval operation during combat. However, simultaneous control of both the air and the water in the area of operations is not necessarily required. Thus, sea control is a selective function that is dependent on the time and scenario and is exercised when deemed necessary. [Ref. 26]

Sea control is achieved by finding, targeting, and attacking enemy surface, subsurface, and airborne threats that could infringe upon the control of an area determined to be vital to carrying out the Navy's mission. Thus, a projection of force, using all assets available, will be used to accomplish these operations. This is referred to as power projection and may entail the employment of a wide spectrum of offensive capabilities that include the use of carrier-based attack and fighter assets. [Ref. 26]

2. Power Projection

To either achieve or maintain sea control, power projection may have to be used. This entails the use of a variety of assets to destroy enemy naval forces either at sea or in their home ports or bases. By preventing the enemy forces from reaching areas deemed critical for sea control, maritime superiority is achieved, thereby allowing friendly forces to access and use sea lanes and airspace vital to conducting operations against the enemy for indefinite periods of time. [Ref. 26]

Power projection can be used to strike both land and sea based targets. In an overland scenario, carrier based aircraft can be used to strike critical targets well inside enemy territory as well as other coastal targets. In conjunction with the aircraft strikes, naval gunfire, surface-to-surface missile attacks, and/or amphibious landings may be used to further weaken the enemy's will to fight. [Refs. 26,27]

B. U.S. NAVY ATTACK AIRCRAFT MISSIONS

The primary functions in support of the Navy's mission, sea control and power projection, call for the employment of a wide variety of assets, including carrier-based attack and fighter aircraft. Today, the Navy's attack aircraft (A-6E, A-7E, F/A-18), support aircraft (E-2C, EA-6B) and fighter aircraft (F-14A, F/A-18) comprise the heart of the carrier's offensive and defensive operations. The carrier relies heavily on these assets and those of other surface units to project the power both in a war-at-sea (WAS) or an overland scenario. [Refs. 1,26,28]

The nature of attack aircraft missions do not change appreciably between the WAS and the overland scenarios. However, specific tactics used during these missions may differ, depending on the nature of the target, the defenses, and possibly the weather.

1. Overland Scenario

Attack aircraft missions associated with an overland scenario generally require the aircraft to ingress to a point target or area of interest, deliver the appropriate ordnance, and return to the aircraft carrier. The exact mission profile used is directly related to survivability concerns and may differ radically, depending on the mission being conducted, the level and sophistication of the threats, and the support provided by other friendly forces. The specific ordnance loads and delivery modes are selected based on several parameters, such as the level of destruction desired (create a few craters or many small craters), the target area weather (use dumb or smart bombs), the type and material composition of the target (hangar or runway; corrugated steel or concrete), and the level and types of threats along both the ingress and egress routes and in the target area. [Ref. 29]

The specific primary missions for attack aircraft in an overland scenario against a major power are suppression of enemy air defense (SEAD), close air support (CAS), coordinated long and short range strikes, interdiction, armed reconnaissance, and rescue combat air patrol (RESCAP). [Ref. 1]

a. Suppression of Enemy Air Defenses

The objective of the SEAD mission is to reduce the attrition of friendly aircraft by attacking SAM or AAA systems either in advance of, or during a strike. The mission is usually conducted by specially configured or equipped aircraft designed to locate, identify, and jam or physically destroy cooperative ground based enemy air defense systems that employ sensors that radiate electromagnetic waves such as a radar. These missions are often referred to as Iron Hand missions and are carried out by the Navy's A-7E Corsair II, the F/A-18 Hornet and the EA-6B ICAP-II Prowler. [Ref. 1]

b. Close Air Support

The CAS mission is designed to assist friendly ground forces in reaching their objectives by harassing or conducting other specific actions against enemy forces. It involves air action against hostile targets that are in close proximity to friendly forces, requiring detailed integration of each air mission or sortie with the fire and movement of these ground forces. The fixed wing aircraft that conduct this mission are the A-6E Intruder, the A-7E and the F/A-18. [Refs. 1,28,29]

c. Coordinated Long and Short Range Strikes

These missions are designed to reduce the enemy's war making ability and logistics and resupply capability through the destruction of specific high value targets. These targets are usually located in heavily defended areas. Destroying, neutralizing, or delaying enemy ground forces will severely impair their ability to bear arms against friendly forces. These missions require the use of many assets and may be flown over very large distances. Attack aircraft tasked with this mission are the A-6E, the A-7E and the F/A-18. [Refs. 1,28,29]

d. Interdiction

Interdiction is designed to destroy, neutralize, delay, or deny the enemy's potential to conduct operations in a particular area. This mission consists of attacking three types of targets selected to control the flow and operation of the enemy in a particular area. The area may include a tactical control point (TCP), a tactical control area (TCA) and/or a designated target (DT). A TCP is a target, such as a road, bridge, or specific point, along a route the enemy may take. Targets in a TCA may include a number of TCP targets. For example, to secure an area for friendly forces to occupy, the destruction of several roads or bridges may be required. A DT is defined as a specific target along the enemy's lines of communication, such as a tank, truck, or convoy. The Navy's attack aircraft that perform this mission are the same as those conducting the coordinated strikes. [Refs. 1,28,29]

e. Armed Reconnaissance

This mission is usually conducted within a particular area or sector where enemy activity is high. It entails striking primarily mobile targets of opportunity, such as trains, shipping, and tanks, and secondarily fixed targets, such as roads and railways, that are key to the enemy's operation in that area. Additionally, intelligence, troop movement, battle force disposition, location, and total strength may also be gathered during this mission. Navy attack aircraft used for this mission are the same as those used to conduct coordinated strikes. [Refs. 1,28,29]

f. RESCAP

This mission uses every asset available to safely and expediently search for and rescue (SAR) a downed aircrew. If conducted in a hostile area, the mission is referred to as combat search and rescue (CSAR). The fixed wing attack aircraft used in this mission are the A-7E and F/A-18. These aircraft are tasked with providing air cover for the searching helicopter that actually does the rescue. [Refs. 1,29]

2. War-at-Sea Scenario

Attack aircraft missions associated with a WAS scenario are unique in that friendly forces must fly into an enemy's defenses instead of making every effort to avoid them. Furthermore, unlike the overland scenarios, there is no terrain to mask the ingress to or egress from the target area. Additionally, the exact location of the enemy naval forces may be difficult to pinpoint resulting in the attack aircraft inadvertently flying into the range of their weapons systems. [Ref. 29]

The objective of a WAS mission is to neutralize enemy offensive capability, degrade enemy sea worthiness, and finally sink enemy ships. The attack aircraft missions in support of WAS scenarios are SEAD, coordinated long and short range strikes, RESCAP, and surface surveillance control (SSC)/Bird Dog. With the exception of SSC/Bird Dog mission, these missions are virtually identical to those described for the overland scenario, but are conducted over water. [Refs. 1,29]

a. SSC/Bird Dog

This mission divides an area around the carrier into smaller specific search areas so that the contacts in this area can be identified and tracked. Based on time on station requirements, weather, and sea conditions, a number of aircraft will be assigned to specific areas to use onboard sensors and data links to relay requested information back to the carrier. Location data on hostile targets located great distances from the task force, often referred to as over-the-horizon targeting, can also be performed by these aircraft. The A-6E, A-7E, F/A-18 as well as most of the fixed wing and helicopter assets on the carrier perform this mission. [Refs. 1,29]

3. Attack Aircraft Missions Against a Third World Nation

In operations against a Third World Nation, the missions of the attack aircraft for both overland and war-at-sea scenarios do not appreciably change. The major differences lie in the amount of territory to be covered, the numbers and sophistication of that nation's land-based and sea-based defenses, and the level and length of operations that are to be conducted against that country. These operations may be over a long period of time, such as Vietnam, or over a period of several hours, such as the April 15, 1986 strike against enemy positions in Lybia. Although the general mission descriptions do not change, the tactics used will most probably be adjusted to account for that country's use of its offensive and defensive assets.

C. U.S. NAVY FIGHTER AIRCRAFT MISSIONS

1. Overland Scenario

The primary mission of fighter aircraft overland is to prevent the enemy from engaging friendly aircraft as they ingress to and egress from the target and to ensure the target area is free from opposing enemy fighters. Fighters may support the strike group in a variety of ways, such as by escorting them, acting in defense roles from standoff positions, and/or offensively protecting them from patrol positions. Some specific missions for fighters include combat air patrol (CAP), fighter sweep, strike escort, and air reconnaissance. [Refs. 1,5]

a. Strike Escort

The objective of this mission is to protect the strike force attack and support aircraft through a variety of escort profiles designed to reduce attrition of friendly aircraft once detected and intercepted by enemy fighters. The Navy's fighters employed in this role are the F-14A and the F/A-18. [Ref. 5]

b. Combat Air Patrol

This mission generally assigns fighters to a specific patrol area for the purpose of intercepting and destroying hostile aircraft or missiles before they reach their target. Many of these CAP missions such as MIGCAP, target CAP (TARCAP), barrier CAP (BARCAP), and force CAP (FORCAP) are specialized, and their specific purpose and objectives are classified. CAP missions are primarily conducted by the Navy's F-14A Tomcat and the F/A-18. [Refs. 1,27]

c. Fighter Sweep

This mission is the dedication of the fighter aircraft to protect or defend attack and support aircraft through the offensive tactic of seeking out and destroying enemy aircraft or targets of opportunity in an allotted area of operation. The Navy's fighters that are employed in this role are the F-14A and the F/A-18. [Refs. 1,5]

d. Aerial Reconnaissance

The objective of this mission is to obtain photography of high interest activity or targets. Specific objectives may be bomb damage assessment (BDA), target photography, or to gather information on enemy activity. The only aircraft in the U.S. Navy's inventory capable of this mission is the tactical air reconnaissance pod system (TARPS) configured F-14A. [Refs. 1,30]

2. War-At-Sea Mission

Fighters in a WAS scenario are primarily dedicated to the maritime air superiority (MAS) mission. The specific details and descriptions of the MAS missions are classified. [Refs. 27,30]

3. Fighter Missions Against a Third World Nation

The same differences and scope of operations for the attack aircraft apply to the fighter aircraft in this type of scenario.

IV. THREAT SYSTEMS DESCRIPTION AND SCENARIOS

Since World War II, the emphasis on improving air defense systems has generated an abundance of highly complex and widely used weapon systems that pose serious threats to tactical aircraft. The tremendous improvements in radar, optical, and IR detecting and tracking methods, missile performance, projectile velocities, and enemy fighter aircraft performance dictate necessary improvements to existing and future friendly attack and fighter aircraft. Thus, an appreciation of threat system capabilities, complexities, and design is necessary to understand the emphasis on increased performance and signature reduction for future attack and fighter aircraft. [Refs. 1,31]

A. THREAT TERMINOLOGY

The threats to an aircraft have been defined as those elements of a man-made nature designed to reduce the flying ability of an aircraft resulting in its inability to perform mission related functions. This is accomplished by employing threat systems designed to inflict damage to an aircraft that either degrades or even destroys the aircraft or by intimidating the pilot into maneuvers that may increase his survivability, but impair his ability to successfully accomplish his objective. [Ref. 1]

In order to survive in an area of hostile air defense threat systems, a thorough knowledge of the threat systems capabilities, location, operational status, and the aircraft's capabilities against them is required. Aircraft capabilities cover multitude of options, such as electronic countermeasures (ECM), tactics with increased aircraft performance, signature reduction or any combination thereof. [Ref. 1]

The principal categories that make up the threat topical field include threat characteristics, operations, and lethality. Threat characteristics refer to the types of threat, threat platform, and propagators used, as well as a description of the warhead. Threat operations refer to the environmental factors and firing or launching capabilities of the threat system, such as its mobility, locational adaptability, and weather capability, as well as the system's slew rate, rate of fire, and target intercept envelope. Threat lethality refers to those factors relating to fire control, propagator trajectory, and the terminal effects parameters of the threat in the process of directing, projecting, and activating one or more damage mechanisms designed to adversely affect the target. [Ref. 1]

With all the categories defined, a generic system mounted on a tracked vehicle might be characterized as an all-weather, highly mobile, terminal threat surface-to-air missile system equipped with a supersonic, high "G," command guided missile armed with a proximity fuze and a 400 lb high-explosive (HE) fragmentation warhead.

1. Surface-to-Air Missile Threats

This particular type of threat, which can be land- or sea-based, is used to launch and guide missiles against airborne targets. The specific launch and guidance equipment varies in size from a single hand-held launch tube to a semi-permanent complex of a variety of trailers, vans, and launch units. [Ref. 1]

SAM systems ranges vary from very short, such as a shoulder fired weapon, to extremely long ranges, as in the case of the Soviet's SA-4 SAM system. In most instances, the enemy will select and locate the SAMs in an attempt to develop the overlapping coverage needed to provide the ground or naval forces with adequate air defense. [Refs. 1, 13]

The initial deployment of the early SAM systems was to fixed positions due to their immobility. The equipment was rather cumbersome, heavy, and required dedicated on-site maintenance. An example was the U.S. Army's Nike Hercules SAM system. Today, with the emergence of computers and extremely fast and reliable digital equipment, much of the bulk and weight have been reduced, resulting in a tremendous increase in system mobility. [Ref. 1]

SAM systems today generally include a dedicated radar for tracking both the missile and the target aircraft. They are normally provided target location information from early warning (EW) and target acquisition (TA) radars. The EW and TA family of radars have very long maximum target detection ranges, but they generally have relatively poor aircraft tracking accuracy due to their lower radio frequencies (RF) and pulse repetition frequencies (PRF), wide beamwidths, and long pulse widths necessary for achieving these long ranges. [Ref. 1]

The target tracking radar (TTR) nominally operates at a relatively high radio frequency, with high PRF's to increase data rates, a small pulse width to improve range resolution for closely spaced targets, and a narrow beamwidth to improve azimuth resolution. Thus, SAM TTRs can be categorized as relatively short ranged, high data rate radars with good target tracking accuracy and resolution tailored to the missile performance and warhead capabilities. [Ref. 1]

Missile guidance is achieved using either a dedicated missile guidance radar or the target tracking radar. A given SAM system may use several types of guidance to conduct an intercept. For most anti-aircraft applications, missile guidance types include command, beam rider, homing, and retransmission. [Ref. 1]

Command guided missiles are those whose guidance instructions or commands originate from sources outside the missile. By using a device, such as a flare or a radar beacon on the missile, to track the missile and a target tracking system using radar, optics, infrared, or lasers to track the target aircraft, appropriate guidance commands may be transmitted to the missile based on target and aircraft ranges, elevations, and bearings. Additionally, information such as fuzing, arming, and warhead detonation may also be passed using this up link. SAM systems using command guidance include the French Crotale, the British Rapier and Soviet land-based SA-2, 3, 4, and 8 and sea-based SA-N-3 and 4 systems. [Ref. 1]

Beam rider missiles use a rearward-facing antenna in the missile to sense the target tracker's signal. By using onboard equipment to determine its position in the TTR's beam, corrections can be calculated and sent to the control surfaces to keep the missile as nearly as possible in the center of the target tracking radar's beam or scanning axis. Since tracking errors for this system relate directly to target tracking accuracy and the TTR's beamwidth, these systems are generally restricted to short ranges. SAM systems using this type of guidance are the British Seaslug, the U. S. Navy's Talos and Terrier system, and the RBS-70, which uses a laser for target tracking. [Ref. 1]

Homing guidance SAM systems comprise three major types: active, semiactive, and passive. They all use a specially configured missile which homes in on electromagnetic energy coming from the target aircraft. The original source of the energy may come from the missile itself (active homing), from a target illuminating radar (semiactive homing), or from the target aircraft itself (passive homing). SAM systems using homing guidance include the U.S. Navy's Sea Sparrow, Standard and Tartar systems, and the U.S. Army's Chaparral, Hawk, Redeye, and Stinger systems, and the Soviet's SA-6, 7 and 9 systems. [Refs. 1, 5,9]

Retransmission guidance is a combination of both command and homing guidance techniques. It is also referred to as track-via-missile (TVM) and is the latest technique developed for guiding missiles to an airborne target. This system typically uses a vastly improved and modernized generation of TTRs designed to track both the target and the missile, illuminate the target, and receive relative target angular position data from the missile. The SAM system then uses computers on the ground to calculate guidance commands for transmission to the missile by the target tracking radar. This closed loop method of guidance allows for tracking and engaging several targets simultaneously. [Ref. 1]

The surface-to-air missiles contain an ordnance package consisting of a fuzed warhead. The fuze package consists of safety and arming devices, a detonator, and a target detecting device (TDD). Fuzing or charge detonation may be accomplished by contact with or proximity to the target. Contact fuzes detonate on or shortly after contact is made with the target and proximity fuzes, often referred to as VT (variable time) fuzing, detonate at some distance from the target aircraft based upon the fuze logic and relative location and motion of the target aircraft. The TDD can be passive, active, or semiactive depending on the nature of the SAM system or the target. [Refs. 1,5]

The types of high-explosive warheads used in these missiles are either blast or pressure, fragmentation, continuous rod, or shaped charge warheads. The primary damage mechanisms causing the damage processes and terminal effects to the aircraft are fragments and to a lesser degree blast. [Refs. 1,5]

2. Surface-to-Air Guns

These land- or sea-based systems vary in size from small caliber shoulder fired guns, commonly referred to as small arms, to rather large fixed site systems, referred to as AAA. Specifically, small arms are those guns that fire projectiles up to and including 20mm in diameter, while AAA fire projectiles greater than 20mm. The primary propagator for these systems is a projectile propelled initially by an applied exterior force that continues its motion by virtue of its own inertia. These projectiles contain an ordnance package consisting of a warhead that is either fuzed, when the warhead has an HE charge, or nonfuzed. The operation of the fuzed warhead is similar to that described for the missiles, but guns include a third type of warhead referred to as the timed-fuzed warhead. The timed-fuzed warhead is set to detonate at a predetermined time following firing. The nonfuzed warhead is a penetrator or kinetic energy penetrator designed to cause damage to the aircraft upon contact. [Ref. 1]

The type of projectile determines its damaging effects. Projectiles fired by gun systems are of the ball (B), armor-piercing (AP), armor-piercing-incendiary (AP-I), and high-explosive type. [Ref. 1]

Generally, the composition and mobility of a gun is a function of the projectile size. AAA systems firing projectiles under 57mm are considered to be extremely mobile for the same reasons SAMs are and are usually widely dispersed throughout an air defense zone. The vast majority of AAA systems consist of several guns, tracking radars or optical devices, associated interface equipment, and projectiles. [Ref. 1]

The range of AAA systems varies with caliber. For example, the 23mm AAA systems are credited with tactical ranges of 1500-2500 meters while the 57mm AAA systems are given a capability out to 6000 meters. Larger caliber AAA systems benefit from increased range, but at the expense of rate of fire. [Ref. 1]

The AAA systems are provided target location information from EW and TA radars for the same reasons SAM radars are. The majority of AAA systems track the target by radar or optical means and use computers to determine a firing solution. Unlike the SAM systems, a guidance or target illuminating radar is not required. However, a few AAA systems today incorporate sophisticated target tracking radars that allow them to accurately track both the target and the projectile with extremely good accuracy. [Ref. 1]

3. Fighter Aircraft

These assets are a class of high-performance aircraft designed to engage and destroy airborne targets. Weapons systems employed by fighter aircraft include air-to-air guns and missiles, and associated equipment for identifying, tracking, and firing the weapons. [Ref. 1]

The range of tactical fighters varies directly with mission requirements, payload, and tanker aircraft availability. Considerable advance in computer controlled flight controls, sophisticated electronics, and weapons have vastly improved fighter effectiveness over the past decade. However, the most severe limitation to these assets is time on station, fuel requirements, and limited numbers of aircraft and ordnance when compared to the ground defenses. [Ref. 1]

Normally fighter aircraft are given vectors to the enemy aircraft by controllers using either a ground controlled intercept (GCI) radar or an airborne command and control aircraft, such as the U.S. Navy's E-2C Hawkeye aircraft. Fighter aircraft then acquire the target using their onboard sensors or visually. The fighter may either prosecute the target in an air-to-air missile engagement and/or an air-to-air gun attack. The air-to-air missiles and guns operate similarly to their land-based counterparts with the exception of the launch or firing origin. [Ref. 1]

4. Lethality

Threat lethality, as it pertains to land- or sea-based SAMs and guns, or air-to-air missiles and guns, is used to refer to the collection of factors that relate to the fire control, the propagator trajectory, and the terminal effects parameters. [Ref. 1]

Fire control factors consist of the types of fire control, the types of coverage, and the types of errors. Types of fire control range from an open sight on small arms and light AAA to an on-mount optical or mechanical lead computing sight to a radar or electro-optical system employed on the larger caliber AAA systems. The types of coverage are aimed fire at a specific target, sector intercept for defense of a sector of the air space, or barrage fire for general coverage of the air space. Fire control errors encompass tracking errors, aiming errors, lead angle prediction errors, and jitter. Tracking errors are introduced by the threat system's inability to accurately provide an exact record of the aircraft flight path. Aiming errors are introduced during the firing or launching phase due to the system's inability to correctly position or aim the appropriate equipment in the desired direction. Lead angle prediction errors result from unexpected target maneuvers during the flight time of the projectile or guided missile. Jitter is produced by the synergistic effects of aiming and tracking errors resulting from rough motion of the weapon system or atmospheric effects. [Ref. 1]

Trajectory factors relate to or influence the missile or projectile path to the aircraft and can be divided into those associated with nonguided and guided propagators. The trajectories of nonguided propagators, such as ballistic projectiles, are affected by gravity drop, ballistic dispersion, and the ballistic coefficient. Gravity drop is caused by the gravitational force on the projectile. Ballistic dispersion is caused by the scatter of the impact points due to differences in weight and surface variations, burning efficiencies, and aerodynamic forces on the projectile. The ballistic coefficient accounts for the attenuation in velocity of the projectile or fragment in transit to the target. Guided propagators are primarily guided missiles whose trajectory is controlled by a guidance package that uses either command guidance, beam-rider guidance, homing guidance and/or retransmission guidance as previously discussed. [Ref. 1]

Missile guidance can be further divided into three phases: boost or launch, which lasts from launch till the booster fuel supply is exhausted; the mid-course phase, which is usually the longest phase in both duration and distance, where course adjustments are made and updated; and the terminal phase which must be the most accurate and rapid to compensate for the dynamic end game. [Ref. 1]

Missile guidance systems are extremely complex and incorporate a balance of guidance types during the three phases to ensure an optimum trajectory is flown. The trajectories are determined by any one of several methods or laws of navigation. The four most common methods are pursuit, lead angle, three point, and proportional navigation. A pursuit trajectory maintains as course by which the missile flies directly toward the target at all times and can be easily thought of as a dog chasing a rabbit. Lead angle trajectory flies the missile on a constant bearing closing range course that results in an eventual intercept with the aircraft. In three-point guidance, the missile is constantly being steered to lie on the line between the target tracking radar and the target aircraft and is most often used in systems employing command to line of sight (CLOS) or beam rider guidance. Proportional Navigation (Pro Nav) is a common method for changing missile heading to cause a target intercept. This is accomplished by attempting to maintain an essentially constant line of sight (LOS) angle by making the rate of change of the missile heading proportional to the rate of change of the LOS. [Ref. 1]

Terminal effects parameters relate to the inherent capability of the damage mechanism to cause damage to a target aircraft. As an example, the terminal effects parameters associated with a blast generated fragment are the fragment's weight and velocity at impact. [Ref. 1]

B. SCENARIO DESCRIPTION

The scenario is a specific description of the many parameters that characterize an encounter between one or more aircraft and the hostile air defensive forces. Key to the scenario are the aircraft flight path(s) and altitudes(s), the number, type, location, employment and operational status of the threats, the environmental and meteorological conditions, and the type of terrain along the ingress, egress, and at the target itself. [Ref. 1]

The following overland and WAS scenarios are generic in nature, but with subtle changes in the variety and sophistication of the threats, the numbers and deployment status of those threats, and the tactics and employment doctrine or philosophy in use, they could represent a scenario against any nation.

1. Overland Scenario

Once the target is either selected or mandated, a decision on the type and amount of ordnance to be used is made. This decision drives the number of attack aircraft that will be used and must be carefully weighed since exposure of the minimum number of aircraft to the enemy's defenses is desired. Parallel to the ordnance planning is the support package planning which focuses exclusively on reducing the strike group's susceptibility to the threats. Decisions on how many jammer aircraft are needed, jamming priorities, and orbit points are made to counter the enemy ground based and airborne threats. Additionally, enemy fighters can pose significant threats to bomb laden attack aircraft and must be neutralized through the use of friendly fighters. Fighter missions (MIGCAP, BARCAP, etc.) are determined, as are the weapons configurations and fuel requirements. Command, control and communications aircraft complete the support package, and decisions with respect to appropriate radio communication and data link frequencies, as well as individual aircraft codes for identification and deconfliction purposes are made.

Once the strike group launches, the attack aircraft and support aircraft execute their missions with enroute decisions made real time, providing the flexibility required to account for any unexpected or unplanned events that might occur during the strike. Attack aircraft loaded with their ordnance ingress to the target, possibly at low altitude to avoid initial detection by the enemy's long range early warning radars. Support aircraft loaded with jamming equipment and anti-radiation missiles attempt to neutralize the enemy's ground based SAM and AAA sites, as well as the critical command and control networks used to control enemy fighters. Terrain is used to mask the attack aircraft from exposure to threat systems until near the target area, where appropriate pop-up maneuvers may be employed to acquire the target. Self-protection equipment onboard the attack aircraft may be used to attempt to neutralize remaining threat systems during the attack phase. Once the ordnance is on target, the strike group may egress high or low, depending on the threats present. Friendly fighters continue to "delouse" the strike group on egress, ensuring enemy fighters are engaged and neutralized before they can achieve a kill against one or more of the attack aircraft. Command and control aircraft that have overseen the entire evolution continue to provide critical "big picture" information, as well as specific information to the attack and support aircraft, maximizing their mutual support. Once safely out of the enemy's air defenses, the attack aircraft will climb to their optimum altitude and return to the carrier along with the fighter and support aircraft.

2. War-At-Sea Scenario

This scenario differs markedly from the overland scenario with respect to the ingress and egress. Unlike the overland scenario, this scenario has very predictable ingress and egress routes that are normally threat free. However, unique to this scenario is the requirement to have very accurate targeting information since the targets are usually always on the move.

Once the targets are assigned, the enemy surface units are studied carefully to assess their offensive capabilities against the carrier task force and their air defense capabilities. The optimum ordnance loads are selected, and the numbers of attack and support aircraft and missions are fixed. Fighter aircraft are most often used as part of the defensive posture assumed by the carrier task force during these operations.

Depending on the location of the enemy forces, the attack aircraft will fly a profile to minimize their exposure to the threat. Command and control aircraft will once again provide the "big picture" to the strike group to maximize coordination. Similar to the overland scenario, support aircraft equipped with anti-radiation missiles and jamming equipment will attempt to roll back the defenses and decrease the attack aircraft's susceptibility. However, ultimately they will need to enter the threat envelopes of the enemy's air defenses. Attack aircraft onboard ECM equipment will be used to degrade the enemy's air defenses. After the ordnance is delivered, egress to the carrier will be at optimum altitude ensuring maximum survivability.

V. SUSCEPTIBILITY ASSESSMENT

A. DEFINITION OF SUSCEPTIBILITY

Susceptibility refers to the inability of an aircraft to avoid being damaged by one or more damage mechanisms in the pursuit of its mission. The degree of susceptibility is dependent on the threat, the scenario, and the aircraft itself. [Ref. 1]

Susceptibility can be measured by P_H, where P_H represents the product of several conditional probabilities that are a function of a particular scenario. For a typical SAM engagement, these may include the probability the threat is active, P_A, the probability the aircraft can be detected, identified and tracked, P_{DIT}, and the probability of a successful missile launch, guidance to an intercept, and warhead detonation, P_{LGD}. Thus, P_H can be written in the form

$$P_H = P_A \; P_{DIT} \; P_{LGD}. \qquad \text{[Ref. 1]}$$

Each one of the probabilities may be influenced by one or more susceptibility reduction features, often referred to as countermeasures. Lately, the emphasis on countermeasures development has received a great deal of attention that is directly related to the intensity of, and needs generated by, recent military operations. Unfortunately, the development and production of countermeasures has tended to lag the development of air-defense weapons. However, through the recent lessons learned in the Southeast Asia conflict, the Arab-Israeli conflicts, and the Falklands, countermeasures are now a major consideration for survivability enhancement in the early design phases of an aircraft. [Ref. 1]

B. SUSCEPTIBILITY REDUCTION FEATURES

Susceptibility reduction features include a wide variety of countermeasures designed to impact primarily radar, infrared, and visually guided threat systems. The majority of these features involve some piece of equipment, device, or armament that is carried by the attacking aircraft for self-protection or by another special purpose aircraft tasked with supporting the attacking aircraft. These features are grouped into the six the concepts of threat warning, noise jammers and deceivers, signature reduction, expendables, threat suppression, and tactics. [Ref. 1]

Specific applications of these features or counter-measures have been developed for the important portions of the electromagnetic spectrum (radar, infrared and visual) and are normally employed for their synergistic degrading effect on enemy air defense systems. The words passive and active are sometimes used to further describe these countermeasure techniques. Passive refers to any technique that does not require any action that would alert the enemy as to the presence of the aircraft. Active, on the other hand, will in most cases compromise the aircraft's position or intent. For example, threat warning and signature reduction are considered passive concepts, whereas noise jammers and deceivers, expendables, and threat suppression countermeasures are usually considered to be active susceptibility reduction concepts. [Ref. 1]

Susceptibility reduction techniques are most effective when used together as complimentary systems to improve the overall net effect. A brief description of each concept and its role with the other concepts will emphasize this point.

1. Threat Warning

Knowledge of the location, type, and status of the threat systems in the vicinity of the aircraft is vital to aircraft survivability. With this information, the pilot could perform an evasive maneuver timed with the delivery of the proper expendable and jamming or deceiving to generate significant errors into the threat system's fire control system resulting in increased miss distances. Thus, with proper warning a combination of several appropriate active and passive techniques can significantly improve the probabilities of survival. [Refs. 1,5,9]

Several types of threat warning systems are needed to adequately warn the pilot to the danger of any combination of radar, infrared, and visually guided threat systems. However, the majority of the threat warning systems in use today are designed to detect only the presence of radar signals associated with SAM, AAA, and airborne threat systems. The two major types of threat warning systems are radar warning receivers and radar homing and warning receivers. These systems can provide vital information, such as threat location relative to the aircraft, threat type, and status (searching, tracking, illuminating, or actively guiding the missile). This information may be displayed to the pilot on a cathode-ray tube (CRT) or through aural warbling tones in headsets or helmets. [Refs. 1,5,9]

Advances in technology have provided the ability to program threat warning systems through software to respond to only those threats stored in the memory. This is extremely useful when trying to match the radar warning requirements to the mission of a particular aircraft. As an example, a low flying attack aircraft may not concern itself with certain surveillance or early warning radars, but aircraft tasked with threat suppression or stand-off jamming may require this type of information. [Refs. 1,9]

Aircrew workload is extremely high in most combat scenarios and results in increased pilot reaction times when confronted with having to make split-second decisions, such as those needed to correctly respond to today's advanced threat systems. Consequently, many of today's electronic countermeasures systems incorporate a power management processor which allows the RWR or RHAW equipment to allocate jamming resources and expendables to priority targets, point any steerable jamming antennas, optimize jamming by selecting the appropriate jamming modulation, and tune jammers to match the measured radar characteristics. Additionally, power management can maximize jamming effectiveness by controlling the jamming duty cycle as well as provide for the simultaneous jamming of several radars in succession through the use of time-gated noise. [Refs. 1, 5,9]

2. Noise Jammers and Deceivers

Onboard or stand-off active electronic equipment designed to degrade the effectiveness of various terminal and nonterminal threat systems is considered critical for aircraft survivability. Onboard equipment used for defensive electronic countermeasures (DECM) against threat systems is usually referred to as a self-screening or self-protection jammers, such as the U.S. Navy's ALQ-165 airborne self-protection jammer (ASPJ). Larger, more capable offboard equipment can be carried either by a drone or a special purpose aircraft, such as the U.S. Navy's EA-6B aircraft. [Refs. 1,5,9]

There are two primary radiation emission techniques used to reduce an aircraft's susceptibility. These are noise or denial jamming and deception jamming. Noise/denial jamming may be thought of as a "brute force" method designed to hide an aircraft's radar echo. Deception jamming is more complex and uses transmitted signals that are designed to confuse or fool the particular threat system radar and not necessarily overpower it, hence the difference between the two techniques. These two techniques are primarily used against radars. However, there are devices designed to jam or deceive other portions of the electromagnetic spectrum, such as the infrared. [Refs. 1,9]

Radar noise jamming consists of generating a noise-like signal with the characteristics of the victim radar that has sufficient energy to mask the aircraft's radar echo presented to the radar operator on the CRT. The majority of the noise used is continuous wave (CW) and may be generated using a variety of techniques. The most common of these techniques are broadband or barrage jamming, spot jamming, and swept jamming. Broadband or barrage jamming is primarily used against a radar whose exact operating frequency is changing or agile. This technique may also be used to cover the operating frequencies of more than one radar. Spot jamming is relatively narrow in its frequency coverage and is used against radars whose frequency is known. Spot jamming uses a bandwidth sufficiently wide enough to cover the victim radar's operating frequency range and is centered at the center of its operating bandwidth. Swept jamming is the rapid, repetitive sweeping of a narrow bandwidth noise signal across the bandwidth of the victim radar and is sometimes used in place of barrage jamming. [Refs. 1,9]

There are two parameters used to determine the effect of noise jamming on a particular radar system. These are the jam-to-signal ratio (J/S) and the burn-through range, R_B. J/S is the ratio of the power of the noise intercepted by the victim radar's receiver to the power of the aircraft's return echo. The power of the noise generated by the jammer, J, may be represented as

$$J = P_j \; B \; G_j$$

where P_j is the jammer power density, B is the bandwidth of the radar receiver, and G_j is the gain of the jammer antenna in the direction of the victim radar. [Ref. 1]

The power of the echo, S, at the target is given by

$$S = (P_r \; G_r \, \sigma)/(4\pi \; R^2)$$

where P_r is the radar power, G_r is the radar's antenna gain, σ is the radar cross section of the target aircraft and R is the aircraft's range from the radar. [Ref. 1]

Dividing J by S will give the J/S ratio at the target and also at the radar receiver for a self-screening situation, and can be mathematically represented as

$$J/S = (P_j\ B\ G_j\ 4\pi\ R^2)/(P_r\ G_r\ \sigma). \quad \text{[Ref. 1]}$$

Burn-through range is the distance from the victim radar at which the target aircraft's radar echo is stronger than the level of jamming present. This can be explained by looking at the J and S equations for an aircraft approaching a particular threat system. As the aircraft range decreases, S becomes larger while J is unaffected. Thus, J is essentially constant, whereas S is inversely proportional to the square of the range of the target aircraft from the victim radar. By defining the minimum J/S ratio as that required to barely mask the target aircraft, and expressing it as a "camouflage factor," C, the burn-through range can be mathematically expressed as

$$R_B = [(P_r\ G_r\ \sigma\ C)/(P_j\ B\ G_j\ 4\pi)]^{.5}.$$

It is important to note that there is not a single value for R_B since the fluctuation in σ and jammer antenna gain, Gj, occur continuously in any typical scenario. [Ref. 1]

Noise jamming may also be provided by dedicated aircraft in a supporting role. These supporting aircraft normally operate at distances from both the target aircraft and the victim radar that are outside the range of enemy air defenses. Inherent advantages to stand-off jammers are the simultaneous protection of several aircraft, higher power, one or more directional antenna, profile optimization to maximize the jammer-to-radar propagation factor, neutralization of home-on-jam tracking, increased asset availability, and concealment of precise direction to the attack aircraft. Disadvantages are the requirement for high jamming power to achieve a desired J/S at these stand-off ranges, difficulty in providing sufficient protection by remaining behind the strike group, and the potential to be targeted as a high value target whose loss will severely impact attack aircraft survivability. [Refs. 1,9]

Equations for calculating J/S ratios and burnthrough ranges for stand-off noise jammers can be derived in a similar manner as those for the self-protection jammer, but must account for the fact that the jammer and target aircraft are not collocated. Thus, the J/S ratio for stand-off noise jammers can be given in the form

$$J/S = (P_j \; B \; G_{jr} \; G_{rj} \; 4\pi \; R_t^{4})/(P_r \; G_r \; G_r \; \sigma \; R_j^{2})$$

where R_t is the radar to target range, R_j is the radar to jammer range, G_{jr} is the gain of the jammer antenna in the direction of the radar, and G_{rj} is the gain of the radar antenna in the direction of the jammer. Burn-through range for a stand-off jammer is obtained by setting J/S = C and solving that equation for Rt. Thus, R_B for the stand-off jammer can be expressed as

$$R_B = (P_r\ G_r^2\ \sigma\ C\ R_j^2/P_j\ B\ G_{jr}\ G_{rj}\ 4\pi)^{.25}.\ \text{[Ref.1]}$$

Many factors play heavily in the operational employment of a jamming system. These include types and numbers of jammers, prioritization of jamming targets, frequencies to be jammed, selection of optimum jamming modulations to be used, and jammer on and off times. To further enhance a jammers effectiveness, most jamming systems either use the RWR or RHAW equipment or some type of "look-through" scheme to gain up-to-date information about the radars to be jammed such as frequency changes, radar on and off modes, and relative bearing to the threat system. [Refs. 1,9]

Deception jammers are considered "smart" jammers whose purpose is to deceive or fool a particular threat system by introducing into the victim radar false target information. This type of jamming may be done against both radar and infrared systems. The general approach to deception jamming is to overload the victim radar by generating a large number of false targets indistinguishable from the real targets and/or provide erroneous target bearing, range, or velocity information to the victim radar. [Refs. 1,5,9]

Deception jammers use a great many techniques, such as range-gate-pull-off (RGPO) and inverse con-scan. RGPO superimposes the deceiving pulse onto the actual target echo, increases the intensity of the superimposed pulse to a level sufficient to capture the victim radar's automatic gain control (AGC), and either delays or advances the now stronger deceiving pulse to move the range gate off the actual target echo. Once the AGC circuit has been captured and the range gate has been moved off the actual target, the deceiving pulse may be shut off, leaving the range gate without a target in it and requiring the victim radar to reacquire the target. [Refs. 1,9]

Inverse con-scan is an amplitude modulation technique used to deceive conical scan tracking radars. This technique uses passive techniques to determine both the scan rate of the radar and when the scanning beam is closest to the aircraft. With this data, it then transmits a very strong deceiving pulse in synchronization with the scan rate, but timed such that the stronger deceiving pulse is transmitted when the victim radar's scanning beam is pointed away from the actual target. As the scanning beam approaches the aircraft, the deceiving pulse is turned off. The net effect is that the victim radar will interpret the inverse modulation pattern to mean the aircraft is in the direction of the deceiving pulse. [Refs. 1,9]

Infrared jammers and deceivers are devices designed to introduce large amounts of infrared noise into an infrared tracking system or to fool these systems by introducing false target information. The principles by which these devices work are similar to their radar counterparts. [Ref. 1]

3. Signature Reduction

A threat system's ability to quickly detect, locate, identify, and accurately track an airborne target will have a direct bearing on its survivability. Reducing aircraft signatures can severely degrade the ability of a threat system to accomplish these functions. Currently, major contributors to an aircraft's overall signature are the radar cross section, its infrared radiation, and the visual and acoustic signatures. The two general methods used to reduce an aircraft's signature are to reduce the aircraft signature to a level below sensor threshold and to mask the aircraft's signature by minimizing the aircraft-to-background contrast. [Ref. 1]

Radar signature reduction is specifically designed to reduce the level of the signature by reflection, absorption, or active interference with surface currents. The objective of reflection is to reflect the radar signal away from the receiving antenna. For most monostatic radar systems, where the transmitting and receiving antenna are collocated, knowledge of the radar's receiver location is not necessary since the received direction is all that is required. However, for bistatic radars, where the transmit and receive antennas are not collocated, information on the location of the radar's receiver antenna is required.

Absorbtion of the impinging radar signal is accomplished using specially designed radar absorbing materials called RAM. RAM can "absorb" the echo either by admitting and then internally attenuating the strength of the impinging signal, or by internally generating reflections that interfere with the reflection from the front surface. Interference with the surface currents is a method used for countering radars whose wavelength is approximately the same or longer than the scattering surface of the aircraft. This is accomplished by introducing impedances at various key locations over the aircraft surface that normally create high RCS signatures. [Refs. 1,16,22]

Infrared signature reduction is a method to control the level of infrared signature presented to a threat system. This is accomplished by reduction of the temperature, reduction or masking of the observable radiating area, reduction of the surface emissivity, and reduction of surface reflectivity. [Refs. 1,10,14]

Visual signature reduction is based on minimizing the contrast between the aircraft and the background with respect to luminance, chromaticity, clutter, and movement. The areas receiving the majority of attention are the engine exhaust and glow, the glint off the canopy, the airframe signature, and the aircraft lighting. [Ref. 1]

Aural signature is the only important signal not in the electromagnetic radiation spectrum. This type of reduction may be accomplished by acoustic power reduction, spectrum shaping, shielding and absorbtion. Examples of acoustic noise reduction for propeller and rotor blades include increasing the numbers of blades and their diameter, decreasing tip velocities, decreasing shaft horsepower, or through phase cancellation in multipropellor aircraft. Spectrum shaping during the conceptual design phase of the aircraft may allow for shaping the noise at frequencies where the human ear is less sensitive. Shielding may require a physical boundary be placed in the path of the noise while absorbing materials, such as fiberglass batting or open-cell polyurethane that absorb incident acoustic energy, might be placed around critical components. [Refs. 1,10]

Other signatures that pose significant potential problems for tactical aircraft are the inadvertent or deliberate active electromagnetic emissions which become sources for detection, tracking, and home-on-jam. Inadvertent emissions include emissions from equipment placed in a standby status that are not sufficiently shielded to prevent extraneous noise from emitting from those systems. Active emissions include radars for navigation and weapons, radar altimeters, radio communications, and active countermeasures, such as jammers and deceivers. [Refs. 1,9]

4. Expendables

Expendables are widely used in tactical aircraft due to their relative low cost, ease of operation, and generic effect. Expendables can be used for self-protection or for the mutual support of many aircraft. They are designed for the purpose of denying or deceiving threat systems for a short period of time. For optimal effectiveness, the signature of the aircraft employing expendables must be carefully examined to ensure the expendable's signature is larger than the aircraft's. [Ref. 1]

Expendables come in many forms such as chaff, retroreflectors, aerosols, and flares. Chaff was first developed for use in WWII by the British to confuse German air defense radars. Chaff consists of dipoles tailored to the needs of the user by "cutting" them to exhibit a radar return or backscatter cross section matching those of the victim radar's wavelength. The magnitude of the backscatter is dependent upon the orientation of these dipoles with respect to the illuminating radar. Chaff can be dispensed individually for self-protection purposes or in bulk, generating a cloud designed to protect several aircraft. Depending on what frequencies are to be jammed or deceived, the chaff may be cut into long ropes for longer radar wavelengths or put into small bundles for the shorter wavelengths. [Refs. 1,9]

Chaff is used against a wide variety of radars ranging from early warning and GCI to missile, SAM, and AAA target tracking radars. Critical to its effectiveness is the bloom time. Whether for creating chaff corridors, chaff clouds, or self-protection purposes, chaff should be dispensed into turbulent air. This will serve to place the chaff and the aircraft in the same range bin of the victim radar. If this does not happen, the radar may not "see" the chaff and will continue to track the target. Its effectiveness is also dependent on aircraft maneuvering subsequent to deployment, radar type, and any electronic counter countermeasures (ECCM) employed by the radar. If the radar is a pulse-Doppler type or one that employs an ECCM technique such as moving target indicator (MTI) signal processing, the chaff's intended effect may be negated since these radars eliminate stationary targets from the operator's scope, such as ground clutter and chaff as it appears seconds after deployment. [Refs. 1,5,9]

Radar reflectors are primarily used in decoys to create targetlike radar echoes. These devices may also be built to create specific target sizes dependent on the radar's frequency. The important requirement for a good radar reflector is that the generated echo approximate the desired target size for the frequency band and viewing angle of the victim radar. Van Atta arrays, Luneberg lens, and corner reflectors are examples of radar reflectors. [Ref. 1]

Aerosols are mists, fog, smokes, clouds, and similar atmospheric disturbances designed to absorb, scatter, or transmit a specific portion of any incident electromagnetic wave. They can be used to hide aircraft from infrared and other electromagnetic wave sensors as well as visually directed threat systems. Aerosol effectiveness is dependent on the level of reduction in the transmitted intensity of the incident electromagnetic wave as it passes through the aerosol. Thus, the level of reduction or extinction is dependent upon the wavelength of the incident wave, and the particle size and refractive index of the particle. [Refs. 1,9]

Flares are a self-protection device designed to counter threats using infrared homing. As the infrared homing missile approaches the aircraft, the flare is dispensed to present a more attractive and realistic target for the missile seeker to lock-on to, thereby increasing the missile's closest point of approach. Several factors such as bandwidth, intensity, burn time, time to reach peak intensity, and deployment parameters must be considered in the design and employment of flares. Aircraft maneuvers after a flare is dispensed, as well as a reduction in power to reduce the aircraft's infrared emissions, may be necessary for the flare to be "seen." Flares are normally dispensed down from areas near the aft of the aircraft, preferably in nonturbulent airflow to minimize the decrease in infrared intensity caused by velocity effects. Care must be taken to optimize dispensing velocity such that sufficient distance exists between the aircraft and the detonating warhead, but not so high as to prevent the missile seeker form responding to the flare as it passes through its field of view (FOV). Additionally, judicious use of engine afterburner is mandatory so that the large increase in infrared emissions do not overpower the flare's intensity and result in a self-defeating maneuver. [Refs. 1,5,9]

Future applications for expendables include the concept of using relatively low-cost drones equipped with active deception jammers flying in formation with the strike group to act as attractive decoys or support jammers for use against threat radar systems. [Ref. 1]

5. Threat Suppression

Threat suppression is comprised of actions taken by friendly attacking forces to deny the enemy use of their systems through physical damage or destruction. Specialized aircraft performing this mission are normally equipped with both passive detection systems capable of intercepting threat radar systems and antiradiation missiles designed to home in on the transmission from a radar antenna. In some scenarios the mere presence of these assets is sufficient cause for a radar not to be used, thereby rendering it inactive. However, physical destruction or damage is the preferred method since intimidation doesn't remove the threat or eliminate its ability to destroy aircraft in subsequent scenarios. [Ref. 1]

6. Tactics

Development of tactics provides to mission planners the choice of optimum flight profiles, operations, and formations for use in striking a particular target. The tactics for a particular scenario are normally a function of the intensity and lethality of the air defenses, the urgency of the mission, types and numbers of aircraft available, terrain, and weather. Optimum tactics are selected to reduce the susceptibility of the aircraft involved by minimizing exposure times to the threat systems without compromising the performance characteristics of the aircraft. Current tactics for attack and fighter aircraft are numerous and include high-speed and low-altitude penetration and egress, jinking maneuvers to defeat fire-control flight path predictors and cause large miss distances, evasive maneuvers to avoid approaching propagators, avoidance of known threat sites, use of stand-off weapons, nap-of-the-Earth flight, terrain masking/following, adverse weather operation and large saturation attacks. In most instances, the friendly forces in a particular scenario will use several of these tactics in an attempt to neutralize the threat systems' abilities while maximizing offensive effectiveness. [Ref. 1]

C. ESSENTIAL ELEMENTS ANALYSIS

Aircraft survivability is strongly influenced by its susceptibility in a particular threat environment. Given a generic land- or sea-based scenario, as described in Chapter IV, a chronological sequence of the chain of events during a scenario can be listed and examined, starting with the final event and proceeding to the initial event. From this list, the critical factors, i.e., the essential events and elements in the scenario, can be identified that could, if unchecked, cause damage to, or the destruction of, the target aircraft. This analysis is referred to as an essential elements analysis. [Ref. 1]

Once the essential events and elements have been identified, the aircraft's ability to survive hinges on its ability to interrupt this chain of events and degrade the element's capabilities. By listing the susceptibility reduction features of the aircraft and assessing their impact on the sequence of events, an estimate of the aircraft's susceptibility can be made. [Ref. 1]

1. A Simple Example of an EEA

To illustrate the EEA process, consider an encounter between a friendly attack aircraft and a sea-based radar directed, command guided SAM. The SAM system will normally engage the attack aircraft once it has been detected, identified as hostile, and tracked to a position where an engagement can be made. The missile will be launched and guided to the attack aircraft using some form of navigation. If the missile comes close enough to the aircraft to cause the SAM's proximity fuze to detonate the warhead, damage may occur to the aircraft from the blast wave and the fragments. [Ref. 1]

The EEA examines the above encounter, starting with the final event, blast wave and/or fragments striking the aircraft, and working backwards in time to the initial event, i.e., the initial detection of the attack aircraft. [Ref. 1]

For the blast wave or fragments to strike the aircraft, the missile must pass sufficiently close to the aircraft for the proximity fuze to detect the target and detonate the HE charge. The damage to the aircraft is directly related to the location of the aircraft and the exploding warhead, to the fragment velocities and spray angles, and to the relative velocity vectors and attitudes of the aircraft and the missile. For the missile to come close enough to cause fuze activation, the missile must be powered and guided to within the effective range of the TDD. For accurate guidance, accurate information relating aircraft and missile relative positions and velocities must be available. This requires the target and missile tracking radar to provide complete and accurate tracking data to the fire control computer. For the tracking radar to obtain this accurate tracking data, the attack aircraft must present a radar return within the operating parameters of the radar that are consistent with the radar's FOV requirements. [Ref. 1]

This example is a very simplified analysis of the chain of essential events. The essential elements identified in this scenario are the missile's guidance package, the fuze's TDD, the target aircraft, the tracking radar, etc. By using a very detailed analysis to determine all of the essential events and elements, and by examining the impact the susceptibility reduction features available to the target aircraft have on the events, an estimate of the military worth of each feature can be made. [Ref. 1]

2. EEAs for Three Specific Scenarios

This report considers three typical scenarios that include engagements of a friendly aircraft by a surface launched, semiactively guided missile equipped with a proximity fuzed, HE fragmentation warhead, by a surface based, radar guided AAA system using AP-I projectiles, and by an enemy fighter using an onboard radar to launch an air-to-air, IR homing missile with a radar proximity fuze.

The results of these EEAs are given in Tables 2 through 7 [Ref. 1]. At the top of each table are the six susceptibility reduction concepts. Because performance is a driving force in tactics development, the concept of tactics will only refer to the impact increased performance has on this concept. On the left side of the table are the essential events determined critical for each engagement in a chronological order beginning with the projectiles or fragments and blast striking the aircraft. To keep the tables unclassified, the degree of degradation these susceptibility reduction concepts have on two subsequent events occurring is not provided; only a brief description of the susceptibility feature considered to have an impact is given. For signature reduction, any impact will be indicated by an "X" which denotes possible impact on target detection or lock-on ranges, and/or tracking capability. [Ref. 1]

It's important to note that these EEAs are done with the assumption that all of the susceptibility reduction concepts and features listed are not indicative of current or projected U.S. Navy aircraft capabilities. Additionally, these EEAs will be conducted with the assumption that the susceptibility reduction features listed in the tables are inherent to the aircraft itself and are not provided by other support aircraft. In other words, this aircraft is performing the mission as an individual entity without the support of any other assets, such as an EA-6B for jamming support, Iron Hand aircraft for added threat suppression, etc.

TABLE 2

SURFACE BASED SAM SYSTEM EEA (WITH THREAT WARNING) [Ref. 1]

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
1 Blast & fragments strike the target aircraft							
2 Missile warhead detonates in vicinity							
3 Radar proximity fuze detects target aircraft		Maneuverability/ Agility	X		DECM	CHAFF	
4 Missile is propelled and guided to the reflected energy source (terminal guidance phase)	RHAW/RWR	Maneuverability/ Agility	X		DECM	CHAFF	ARMS
5 Missile seeker locks onto reflected energy from target aircraft					DECM	CHAFF	ARMS
6 Missile rearward-facing receivers detect the target illumination signal (midcourse guidance phase)	RHAW/RWR	Maneuverability/ Agility					ARMS
7 Missile is propelled during boost phase							

TABLE 2 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
8 Missile is launched (boost phase)	RHAW/RWR	Maneuverability/ Agility	X		DECM	CHAFF	ARMS
9 Target illuminating radar illuminates target aircraft		Maneuverability/ Agility	X		DECM	CHAFF	ARMS
10 Target aircraft enters max firing range determined by fire control computers	RHAW/RWR	Maneuverability/ Agility			DECM	CHAFF	ARMS
11 Target aircraft is acquired and tracked by the TTR	RHAW/RWR	Speed Maneuverability/ Agility	X		DECM	CHAFF	ARMS
12 Target aircraft enters SAM's TTR maximum detection range			X				
13 SAM TTR slewed to target aircraft's position							
14 Target aircraft's position handed over to designated SAM system TTR for engagement							
15 Decision is made to engage target aircraft with a SAM							

TABLE 2 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
16 Fully operational SAM available to engage target aircraft							ARMS
17 Target aircraft confirmed as hostile							
18 Enemy C^3 network is fully operational							
19 Target aircraft acquired and tracked by the target acquisition radar			X				
20 Target aircraft enters the target acquisition radar's max detection range			X				
21 Target aircraft data is passed to the target acquisition radar							
22 Decision is made to handover target aircraft to a target acquisition radar							
23 Aircraft is designated hostile							
24 Enemy's C^3 network is fully operational							
25 Aircraft detected and tracked by the EW radar			X				

TABLE 2 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
26 Aircraft enters EW radar's max detection range			X				
27 Fully operational long range early warning (EW) radar available							
28 Aircraft breaks radar horizon of enemy's radar and surveillance network							
29 Enemy is in an alert status							

TABLE 3

SURFACE BASED SAM SYSTEM EEA (WITHOUT THREAT WARNING) [Ref. 1]

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
1 Blast & fragments strike the target aircraft							
2 Missile warhead detonates in vicinity							
3 Radar proximity fuze detects target aircraft			X				
4 Missile is propelled and guided to the reflected energy source (terminal guidance phase)			X				ARMS
5 Missile seeker locks onto reflected energy from target aircraft							ARMS
6 Missile rearward-facing receivers detect the target illumination signal (midcourse guidance phase)							ARMS
7 Missile is propelled during boost phase							

TABLE 3 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
8 Missile is launched (boost phase)			X				ARMS
9 Target illuminating radar illuminates target aircraft			X				ARMS
10 Target aircraft enters max firing range determined by fire control computers							ARMS
11 Target aircraft is acquired and t[illegible]cked by the TTR			X				ARMS
12 Target aircraft enters SAM's TTR maximum detection range			X				
13 SAM TTR slewed to target aircraft's position							
14 Target aircraft's position handed over to designated SAM system TTR for engagement							
15 Decision is made to engage target aircraft with a SAM							

TABLE 3 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
16 Fully operational SAM available to engage target aircraft							ARMS
17 Target aircraft confirmed as hostile							
18 Enemy C^3 network is fully operational							
19 Target aircraft acquired and tracked by the target acquisition radar			X				
20 Target aircraft enters the target acquisition radar's max detection range			X				
21 Target aircraft data is passed to the target acquisition radar							
22 Decision is made to handover target aircraft to a target acquisition radar							
23 Aircraft is designated hostile							
24 Enemy's C^3 network is fully operational							
25 Aircraft detected and tracked by the EW radar			X				

TABLE 3 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
26 Aircraft enters EW radar's max detection range			X				
27 Fully operational long range early warning (EW) radar available							
28 Aircraft breaks radar horizon of enemy's radar and surveillance network							
29 Enemy is in an alert status							

TABLE 4

SURFACE BASED AAA EEA (WITH THREAT WARNING) [Ref. 1]

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
1 Projectile penetrates target aircraft							
2 Projectile flies ballistically towards collision point with target aircraft							
3 Projectile is fired at aimpoint based on fire control solution							
4 Target aircraft enters the maximum lethal range of the AAA system							
5 AAA system's gun is initially slewed and continually pointed in direction of aimpoint	RHAW/RWR	Maneuverability Agility	X		DECM	CHAFF	ARMS
6 AAA gun is synchronized with the system's TTR							
7 AAA gun is loaded and available for engagement of target aircraft							ARMS
8 Aimpoint determined by the AAA system's fire control computer	RHAW/RWR	Speed Maneuverability Agility	X		DECM	CHAFF	ARMS
9 AAA system's TTR acquires and tracks the target aircraft	RHAW/RWR	Speed Maneuverability Agility	X		DECM	CHAFF	ARMS

TABLE 4 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
10 Target aircraft enters TTR max detection range			X				
11 AAA TTR radar is slewed to target aircraft's position							
12 Target aircraft's position is passed to AAA's TTR							
13 Decision is made to engage target aircraft with AAA system							
14 Fully operational AAA system is available for target engagement							ARMS
15 Target aircraft confirmed as hostile							
16 Enemy's C^3 network is fully operational							
17 Target aircraft is acquired and tracked by the target acquisition radar			X				
18 Target aircraft enters the target acquisition radar's max detection range			X				

TABLE 4 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
19 Decision is made to handover target aircraft to target acquisition radar							
20 Aircraft determined and designated hostile							
21 Enemy's C^3 network is fully operational							
22 Aircraft detected and tracked by the EW radar			X				
23 Aircraft enters EW radar's max detection range			X				
24 Fully operational long range early warning (EW) radar is available							
25 Aircraft breaks radar horizon of enemy's radar and surveillance network							
26 Enemy is in an alert status							

TABLE 5

SURFACE BASED AAA EEA (WITHOUT THREAT WARNING) [Ref. 1]

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
1 Projectile penetrates target aircraft							
2 Projectile flies ballistically towards collision point with target aircraft							
3 Projectile is fired at aimpoint based on fire control solution							
4 Target aircraft enters the maximum lethal range of the AAA system							
5 AAA system's gun is initially slewed and continually pointed in direction of aimpoint			X				
6 AAA gun is synchronized with the system's TTR							
7 AAA gun is loaded and available for engagement of target aircraft							
8 Aimpoint determined by the AAA system's fire control computer			X				ARMS
9 AAA system's TTR acquires and tracks the target aircraft			X				ARMS

TABLE 5 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
10 Target aircraft enters TTR max detection range			X				
11 AAA TTR radar is slewed to target aircraft's position							
12 Target aircraft's position is passed to AAA's TTR							
13 Decision is made to engage target aircraft with AAA system							
14 Fully operational AAA system is available for target engagement							ARMS
15 Target aircraft confirmed as hostile							
16 Enemy's C^3 network is fully operational							
17 Target aircraft is acquired and tracked by the target acquisition radar			X				
18 Target aircraft enters the target acquisition radar's max detection range			X				

TABLE 5 (CONTINUED

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
19 Decision is made to handover target aircraft to target acquisition radar							
20 Aircraft determined and designated hostile							
21 Enemy's C^3 network is fully operational							
22 Aircraft detected and tracked by the EW radar			X				
23 Aircraft enters EW radar's max detection range			X				
24 Fully operational long range early warning (EW) radar is available							
25 Aircraft breaks radar horizon of enemy's radar and surveillance network							
26 Enemy is in an alert status							

TABLE 6

AIR-TO-AIR ENGAGEMENT EEA (WITH THREAT WARNING) [Ref. 1]

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
1 Blast and fragments strike the target aircraft							
2 Missile warhead detonates in the vicinity							
3 Radar proximity fuze detects target aircraft		Maneuverability/ Agility	X				
4 Missile is propelled and guided to the IR source (boost, midcourse and terminal guidance phases)	RHAW/RWR	Maneuverability/ Agility	X	X	DECM	CHAFF FLARES	
5 Missile is launched		Maneuverability/ Agility		X		FLARES	
6 Missile seeker locks on to target aircraft's IR radiation source(s)		Speed, Maneuverability/ Agility		X		FLARES	
7 Target aircraft engine(s) are within missile seekers field of view		Speed, Maneuverability/ Agility		X			

TABLE 6 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
8 Fighter aircraft proceeds to a position for maximum range launch at target aircraft	RHAW/RWR	Speed, Maneuverability/ Agility	X	X	DECM	CHAFF	
9 Fighter aircraft onboard radar locks on to target aircraft		Speed, Maneuverability/ Agility	X		DECM	CHAFF	
10 Fighter aircraft vectored by GCI to acquire target aircraft with onboard radar			X				
11 Fighter aircraft launched to intercept target aircraft							
12 Fully operational fighter aircraft available to intercept target aircraft							
13 Aircraft designated as hostile							
14 Enemy's C^3 network fully operational							
15 Target aircraft detected and tracked by GCI radar			X				

TABLE 6 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
16 Target aircraft enters GCI radar's max detection range			X				
17 Target aircraft data passed to GCI radar							
18 Decision is made to handover target aircraft to a GCI radar for fighter intercept							
19 Fully operational ground controlled intercept (GCI) radar available to track target aircraft							
20 Aircraft determined and designated hostile							
21 Enemy's C^3 network is fully operational							
22 Aircraft detected and tracked by an EW radar			X				
23 Aircraft enters EW radar's max detection range			X				

TABLE 6 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
24 Fully operational long range EW radar available							
25 Aircraft breaks radar horizon of enemy's radar and surveillance network							
26 Enemy is in alert status							

TABLE 7

AIR-TO-AIR ENGAGEMENT EEA (WITHOUT THREAT WARNING) [Ref. 1]

Essential Events / Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
1 Blast and fragments strike the target aircraft							
2 Missile warhead detonates in the vicinity							
3 Radar proximity fuze detects target aircraft			X				
4 Missile is propelled and guided to the IR source (boost, midcourse and terminal guidance phases)			X	X			
5 Missile is launched				X			
6 Missile seeker locks on to target aircraft's IR radiation source(s)				X			
7 Target aircraft engine(s) are within missile seekers field of view				X			

TABLE 7 (CONTINUED)

Essential Events \ Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
8 Fighter aircraft proceeds to a position for maximum range launch at target aircraft				X			
9 Fighter aircraft onboard radar locks on to target aircraft			X				
10 Fighter aircraft vectored by GCI to acquire target aircraft with onboard radar			X				
11 Fighter aircraft launched to intercept target aircraft							
12 Fully operational fighter aircraft available to intercept target aircraft							
13 Aircraft designated as hostile							
14 Enemy's C^3 network fully operational							
15 Target aircraft detected and tracked by GCI radar			X				

TABLE 7 (CONTINUED)

Essential Events / Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
16 Target aircraft enters GCI radar's max detection range			X				
17 Target aircraft data passed to GCI radar							
18 Decision is made to handover target aircraft to a GCI radar for fighter intercept							
19 Fully operational ground controlled intercept (GCI) radar available to track target aircraft							
20 Aircraft determined and designated hostile							
21 Enemy's C^3 network is fully operational							
22 Aircraft detected and tracked by an EW radar			X				
23 Aircraft enters EW radar's max detection range			X				

TABLE 7 (CONTINUED)

Essential Events / Enhancement Concepts	Threat Warning	Tactics (Increased Performance)	Signature Reduction RCS	Signature Reduction IR	Noise Jammers and Deceivers	Expendables	Threat Suppression
24 Fully operational long range EW radar available							
25 Aircraft breaks radar horizon of enemy's radar and surveillance network							
26 Enemy is in alert status							

VI. CONCLUSIONS AND SUMMARY

The purpose of this study was to investigate the impact the six susceptibility reduction concepts of threat warning, tactics, signature reduction, noise jammers and deceivers, expendables, and threat suppression had on aircraft survivability, with particular emphasis on both increased aircraft performance (tactics) and signature reduction (RCS and IR). The conclusions and summary made are based on the EEAs conducted in the study.

A. CONCLUSIONS

1. Threat Warning

The relative impact threat warning information provided by onboard RHAW or RWR equipment has on many aspects of an aircraft's susceptibility is significant, irrespective of the scenario. Without threat warning available, the aircrews may not be aware of, or alerted to, the enemy's presence and/or intent, thereby severely degrading their opportunity to use noise jammers and deceivers, DECM, expendables, and tactics to counter the threat.

2. Increased Aircraft Performance

Increased aircraft performance, with threat warning, has the greatest relative impact in the air-to-air scenario. Once alerted to the presence of an enemy fighter by onboard threat warning equipment or possibly by an onboard radar, the added speed, maneuverability, and agility can be quickly translated into maneuvers and tactics effectively taking advantage of the tactical situation. If equipped with air-to-air missiles or guns, engagement of the enemy may be possible. Additionally, the added performance, maneuverability, and agility provide a capability to evade, avoid, or degrade through the use of chaff, flares, and/or DECM, a possible engagement by the enemy fighter.

Increased aircraft performance, with threat warning, has a similar impact on the SAM and AAA essential events during the surface based scenarios. If equipped with ARMs, elimination of, or infliction of, damage to some of the enemy's air defense radars may be possible. Additionally, timely defensive maneuvers can be used in conjunction with onboard DECM and expendables to preclude, degrade, or terminate an engagement by either threat system.

Increased performance, with threat warning, may also aid in reducing an aircraft's susceptibility by improving the effectiveness of onboard countermeasures, such as DECM, chaff, and flares, whose effectiveness is increased by maneuvering during employment. The aircraft maneuvering may decrease chaff bloom time, or give better positioning of a flare in the threat system's FOV, thereby increasing the effectiveness of both countermeasures techniques.

Increased aircraft performance, with threat warning, plays a more important role during the threat engagement phase of each scenario, i.e., when the TTR attempts to acquire the aircraft, than in the earlier phases. Because the onboard RHAW and RWR equipment provides information only on threat radar tracking systems, timely information about the target acquisition and early warning radars is usually not readily available. If this information was available during the early phases of each scenario, steps might be taken to take advantage of the aircraft's increased performance to increase speed through a particular area, thereby reducing the time spent in that area, or to quickly maneuver to alter the aircraft's route of flight to avoid known enemy activity. Furthermore, early positioning of the aircraft through increased speed and maneuverability for the most effective and efficient maximum range usage of the aircraft's offensive weapons capability can also be accomplished to maximize mission effectiveness.

3. Signature Reduction

Signature reduction, with or without threat warning, has a very significant impact on the essential events irrespective of scenario. This independence of threat warning is due to the fact that signature reduction features are built-in the aircraft and are predominantly "install and forget" features, such as shaping and the use of RAM. The impact both RCS and IR signature reduction have on reducing an aircraft's susceptibility compliments, or in some cases fills gaps in the onboard countermeasures capabilities. This conclusion assumes the signature reduction efforts effectively cover the required frequency bands, such as the TTRs, as well as those for the TA and EW radars.

B. SUMMARY

The conclusions drawn in this study represent only a small spectrum of the possible impacts increased aircraft performance and signature reduction (both RCS and IR) have on survivability. Because of the intent to keep the classification of this report at the unclassified level, open source literature precludes a total evaluation of the relative impacts. However, the results of this study show that both increased aircraft performance, with threat warning available, and signature reduction, with or without threat warning available, increase an aircraft's survivability through a reduction in it's susceptibility. Further study at a higher classification level may possibly reveal the tradeoffs that must be made to achieve the optimum levels of increased aircraft performance and/or signature reduction. Additionally, a better understanding of the effectiveness of these two susceptibility reduction concepts, their impact on the other susceptibility reduction concepts, and their impact on aircraft design and survivability may be possible.

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